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Water Resources Paper 5

Case Histories in the Application of Geophysics to Ground Water Problems

WATER RESOURCES PAPER 5

CASE HISTORIES IN THE APPLICATION OF GEOPHYSICS TO GROUND WATER PROBLEMS

by

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PREFACE

Although geophysical techniques have been used for many years in ground-water problems, their application in hydrogeology has never been as intensive as in the mining and petroleum industries. Because of the different scales of financial returns from successful exploration programs for water resources as opposed to those for metallic and hydrocarbon resources, a great deal more money and effort have been expended by the mining and oil industries in research and development of sophisticated geophysical techniques. Consequently, the geophysical techniques commonly applied to ground-water problems have largely been adopted from the mining and petroleum industries.

However, as ground-water resources take on an increasing importance in urban and industrial development, ground-water geophysics will become more of a separate sub-discipline with specialized research aimed specifically at the problems involved in applying geophysics to hydrogeology. Such research will be justified as the present techniques find wider and wider application, increasing the experience and confidence of hydrogeologists in these techniques, as well as suggesting the development of new geophysical methodology.

This publication is intended to serve as information which hopefully will help create an awareness in interested hydrogeologists of some of the capabilities of and present state-of-the-art in ground-water geophysics. It is organized as a series of five case histories, each of which highlights a particular technique or a particular problem. Part I deals with the use of ground electrical and seismic methods in reconnaisance prospecting for sand and gravel deposits as potential aquifers. Part II involves the use of seismic refraction in mapping bedrock depths as part of a ground-water survey. Part III reports the use of surface electrical methods to a ground-water contamination problem in which salt was leached into a sandy aquifer. Part IV involves a rather specialized case in which magnetic methods were used to search for buried fuel storage tanks thought to be the source of fuel contaminating an aquifer. Finally, Part V is an example of a situation where well logging proved useful in water-supply development.

These case histories exemplify several different situations in which geophysical techniques were successful in saving time and money. It is hoped that they will help hydrogeologists to decide whether or not geophysics would be fruitfully applied in particular projects.

G. H. Mills, Director
Water Resources Branch

March 1, 1975

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Page

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PART I

A RESISTIVITY AND SEISMIC REFRACTION SURVEY FOR DETERMINING THE LOCATION AND DISTRIBUTION OF SAND AND GRAVEL DEPOSITS AS POTENTIAL AQUIFERS IN THE EAST AND MIDDLE OAKVILLE CREEKS BASIN

A RESISTIVITY AND SEISMIC REFRACTION SURVEY FOR DETERMINING THE LOCATION AND DISTRIBUTION OF SAND AND GRAVEL DEPOSITS AS POTENTIAL AQUIFERS IN THE EAST AND MIDDLE OAKVILLE CREEKS BASIN

INTRODUCTION

Exploration for ground water often involves the finding and tracing of sand and gravel deposits because they are of primary importance as potential aquifers. Often, such deposits lie in buried channels in the bedrock, so that determination of the bedrock topography under the overburden is useful in the search for aquifers.

In practice, it has been found that the seismic refraction technique is very useful in determining depths to bedrock or other refractors that have distinct velocity contrasts with overlying materials. However, as different materials in the overburden often exhibit small velocity contrasts, seismic refraction by itself cannot always be used to distinquish between these materials. In some cases, electrical resistivity methods may be applicable because of characteristic resistivity contrasts which are often present amongst overburden materials. The conjunctive use of seismic refraction and resistivity methods has therefore been a common approach used in surveys to determine depths to bedrock and to investigate overburden characteristics.

For determining the location and distribution of sand and/or gravel deposits at depth, possibly in suspected or previously-outlined buried channels, electrical resistivity methods are particularly useful because of the considerably higher resistivities exhibited by sand and gravel above those of other materials (clays, some tills, shales).

However, electrical methods for finding and tracing such coarse-grained overburden deposits at depth will provide good results only when the resistivities of the deposits being sought is in strong contrast with both the bedrock and other overburden materials. If a sand or gravel deposit has its resistivity contrast lowered because of contamination by clay, it will not likely be distinguished from glacial till by resistivity methods alone. The recognition of sands and gravels deposited over shallow bedrock through high resistivities also becomes difficult when the bedrock itself exhibits high resistivities, for example, as do Precambrian and limestone-dolomite rock types. When clean deposits of sand or gravel are located within tills and clays which are underlain by relatively conductive shales, then electrical methods can be used successfully to determine their locations.

RESISTIVITY METHODS - THEORETICAL CONSIDERATIONS

In all electrical methods, DC or low frequency (.3 to 5 hertz) AC current is driven into the ground through galvanic contacts called current electrodes. This sets up a potential field in the ground. The potential is measured by other electrodes called potential electrodes. Knowing the potential and the current, an apparent resistivity reflecting the true resistivities of the ground can be calculated.

There are two basic applications of resistivity techniques:

1. for investigating the depth variation and bedding structure of flat-lying formations, and
2. for fast reconnaisance mapping and profiling in the area under study.

To determine the lithologic variation with depth under specific locations on the ground surface, the Vertical Electrical Sounding (VES) technique is used. Because the depth of investigation of an electrical technique is a function of the electrode separation, by systematically expanding the electrode spacing about a fixed point, the apparent resistivities of materials from progressively greater depths are obtained. By assuming no lateral changes in lithology, a graph of apparent resistivity versus electrode spacing can be made and interpreted quantitatively to determine the thicknesses, depths and resistivities of subsurface formations.

If reconnaisance mapping of resistivities is required, a considerably simplified version of VES called Resistivity Sounding-Profiling (RSP) is used. In this method a number of measurements are made at fixed intervals along a traverse, resulting in a profile of resistivity values. If desired, a number of such profiles can be put together to form a map on which contours of isoresistivities may be drawn. The theoretical depth of investigation of the reconnaissance technique is usually fixed by using a constant electrode separation. Some difficulties in interpretation of ambiguities arising from this kind of survey are often reduced by using two or more electrode spacings, thus obtaining resistivity information from two or more corresponding depths. The results from RSP are less detailed vertically, but it is a much faster method than VES for covering ground laterally.

Several types of electrode arrays can be used for both sounding and profiling. These involve different numbers of electrodes in various geometrical configurations. The more common arrays consist of four electrodes, two current and two potential. The most widely used of these are the Wenner and Schlumberger arrangements, where two potential electrodes are situated between the two current electrodes (see Figure I).

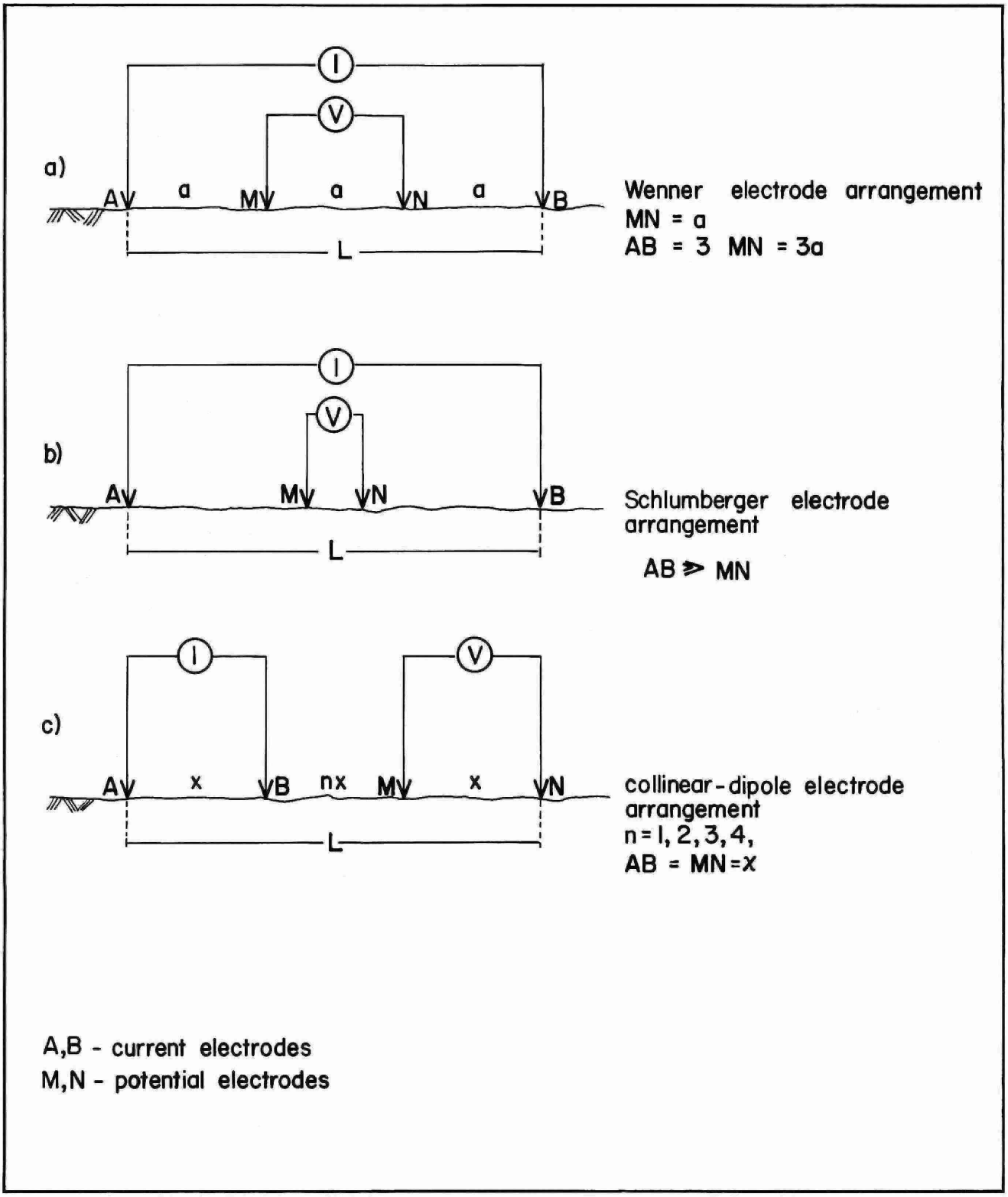

Figure I. Sketches of a) Wenner, b) Schlumberger, and c) collinear-dipole electrode arrangements.

Another common type of electrode arrangement is the dipole-dipole array. It consists of a receiving dipole (V), that is, two potential electrodes, and a transmitting dipole (I), two current electrodes. There are several kinds of dipole-dipole electrode arrangements, each with a different orientation of dipoles with respect to each other. The most common is the collinear-dipole array shown in Figure I. Another term used for this array is "polar dipole" (Zohdy, 1969; Roy and Apparao, 1971).

Comparison of the Collinear-Dipole, the Wenner and Schlumberger Arrays

In order to effectively use the various configurations in geophysical field work, one must know the relative advantages and disadvantages of each. The major factors governing the choice of a particular electrode arrangement are:

(a) its depth of investigation,
(b) its vertical resolution,
(c) its sensitivity to lateral changes in surficial materials, and,
(d) its ease and speed of application and interpretation in the field.

Each of the above will be explained in more detail.

(a) Depth of investigation - the depth of investigation is defined by Roy and Apparao (1971) as that depth at which a thin horizontal (that is, parallel to the surface) layer of ground contributes the maximum amount to the total measured signal at the ground surface. If deep structures are being investigated, then the depth of investigation is of prime importance in choosing an electrode array.

(b) Vertical resolution - the vertical resolution can be defined as the ability of the array to differentiate between two materials exhibiting different resistivities. The smaller the difference in resistivities, the more difficult is the differentiation and the more resolutive the electrode arrangements required.

(c) Sensitivity to lateral changes in surficial materials - to study the layering of materials, that is, to obtain information in the vertical direction, the assumption is made that the resistivity of particular layers does not change in the horizontal direction. This, however, is an over-simplification of the real situation. To deal with resistivity changes in the vertical direction only, that is, for sounding purposes, the electrode arrangement least sensitive to horizontal changes should be used. However, if lateral changes are sought, then the array most sensitive to lateral variations must be chosen.

TABLE 1: Comparison of Wenner, Schlumberger and Collinear-Dipole Electrode Arrangements

Electrode Arrangement	Depth of Investigation	Vertical Resolution	Sensitivity to Lateral Change
Wenner	0.11 L*	Highest	More sensitive than Schlumberger
Schlumberger	0.125 L	High	Least sensitive
Collinear-dipole	0.195 L	High	Most sensitive

* Distance "L" is defined as the distance in any arrangement between the two, extreme, active electrodes; see Figure I.

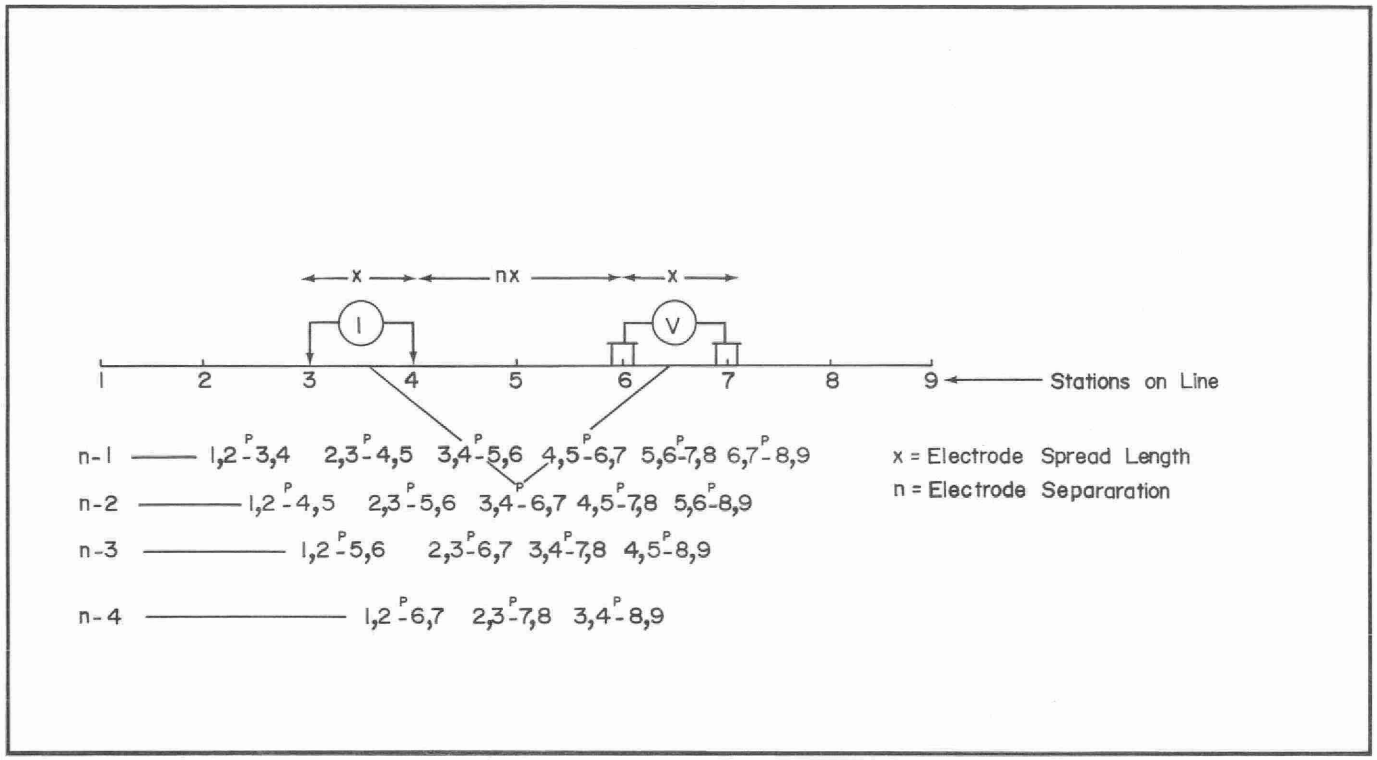

Figure II. Electrode configuration and method of plotting for the collinear-dipole electrode arrangement.

(d) Ease and speed of application and interpretation in the field - usually the easier and faster the technique used, the less costly is the survey. In ground resistivity methods, however, speed is often gained only at the expense of detail. If precise, unambiguous interpretations are required, then time should be taken to obtain detailed measurements. If a large area must be mapped and only gross features are of interest, then a fast easy technique should be used.

Thus, it is obvious that the relative importance given to each of the four factors above will dictate the type of survey undertaken and the electrode separation used. Table I, based on the results of Roy and Apparao (1971), indicates that the collinear-dipole array has the deepest depth of investigation of the three most common configurations. In field practice, this means that with the collinear-dipole array, the investigation of materials to a certain depth may be achieved with a separation (L) about half that for the Wenner and Schlumberger arrays. The most resolutive of the arrays is the Wenner, so that for detailed sounding in laterally homogeneous ground, one would choose this array. The least sensitive to lateral changes is the Schlumberger, so that it is the most useful for sounding over ground where the overburden or solum has a "patchy" composition.

All three are about equally fast for strictly sounding applications. The interpretation techniques are more precise and considerably faster for Wenner arrays; therefore, one would choose the Wenner configuration for VES surveys. For reconnaisance work, where profiling and a crude sounding is needed (RSP applications), the collinear-dipole array is the fastest since the array is moved one interval ahead along the profile merely by "leap-frogging" the last electrode. Changes to different sounding depths can be achieved by reconnecting one electrode (see Figure II). As one of the purposes of mapping or profiling is to detect lateral changes, the fact that the collinear-dipole array is the most sensitive to lateral changes (Table 1) is another advantage in using it for RSP surveys.

THE COLLINEAR-DIPOLE ARRAY IN RSP SURVEYS

The collinear-dipole array appears to be the most suitable for RSP purposes. The method as described by Bodmer and Ward (1968) is briefly explained here. Figure II illustrates the electrode configuration, the field technique used and the standard method of plotting the apparent resistivities.

Both the transmitting (I) and receiving (V) dipoles have the same width x. The dipole width x is chosen according to the probable sizes, depths and resistivity contrasts of geological boundaries. An optimum width should be as large as possible

for economical reasons, but it must be small enough to assure a reliable recognition of anomalies caused by features of interest. The separations between the dipoles are n times x, where n = 1,2,3,4, ..., etc. This makes for a fast and easy placement of electrodes (see Figure II). A current (I) is made to flow into the ground from the transmitting dipole, and the first measurements of potential difference (V) is made between the two electrodes of the receiving dipole; subsequent measurements are made at n = 2,3,..., etc. This represents the sounding part of the technique. The dipole which has been stationary for these measurements is then moved forward one interval to the next station by "leap-frogging". For example, if the receiving dipole is moved forward, as in Figure II, then the electrode at Station 6 is moved to Station 8 - it is "leap-frogged" over the electrode at Station 7. At the new station, the n measurements for sounding are taken, and the profiling procedure is followed until the required length of traverse has been covered.

From the measured potential difference and the current, the true resistivity of a homogeneous half-space, that is, a uniform earth, can be found. If the ground is not uniform, for example, if it is layered, the apparent resistivity of the ground can be found. The apparent resistivity reflects the true resistivities of the ground, and may be calculated from the measurements of V and I according to the following formula (Bodmer and Ward, 1968):

$$R = 6.28 \frac{V}{I} \frac{n(n+1)\ (n+2)x}{2}$$

where R is the apparent resistivity, and x is the dipole width.

If distances are measured in feet, voltages in volts, currents in amperes, then the apparent resistivities are in units of ohm-feet. The values of R are plotted at the intersection of lines drawn at 45° to the horizontal from the centres of the dipoles (see Figure II). Thus, the depth of the plotting point is a very rough estimate of the depth of investigation. The final result is a matrix of resistivities in section along the traverse. These can be contoured to reveal resistivity patterns.

Generally, results from electrical methods are interpreted by comparison with measurements from scale models or with theoretical calculations. Specifically, the collinear-dipole RSP data from relatively simple geologic situations yield coherent patterns whose significance in relation to the geometry of a geological body has been studied by using scale models. As well, Bodmer and Ward (1968) have given a procedure for quantitative interpretation based on theoretical type curves for a single layer over a uniform ground. Both these methods are precise for quantitative evaluation in relatively uncomplicated situations.

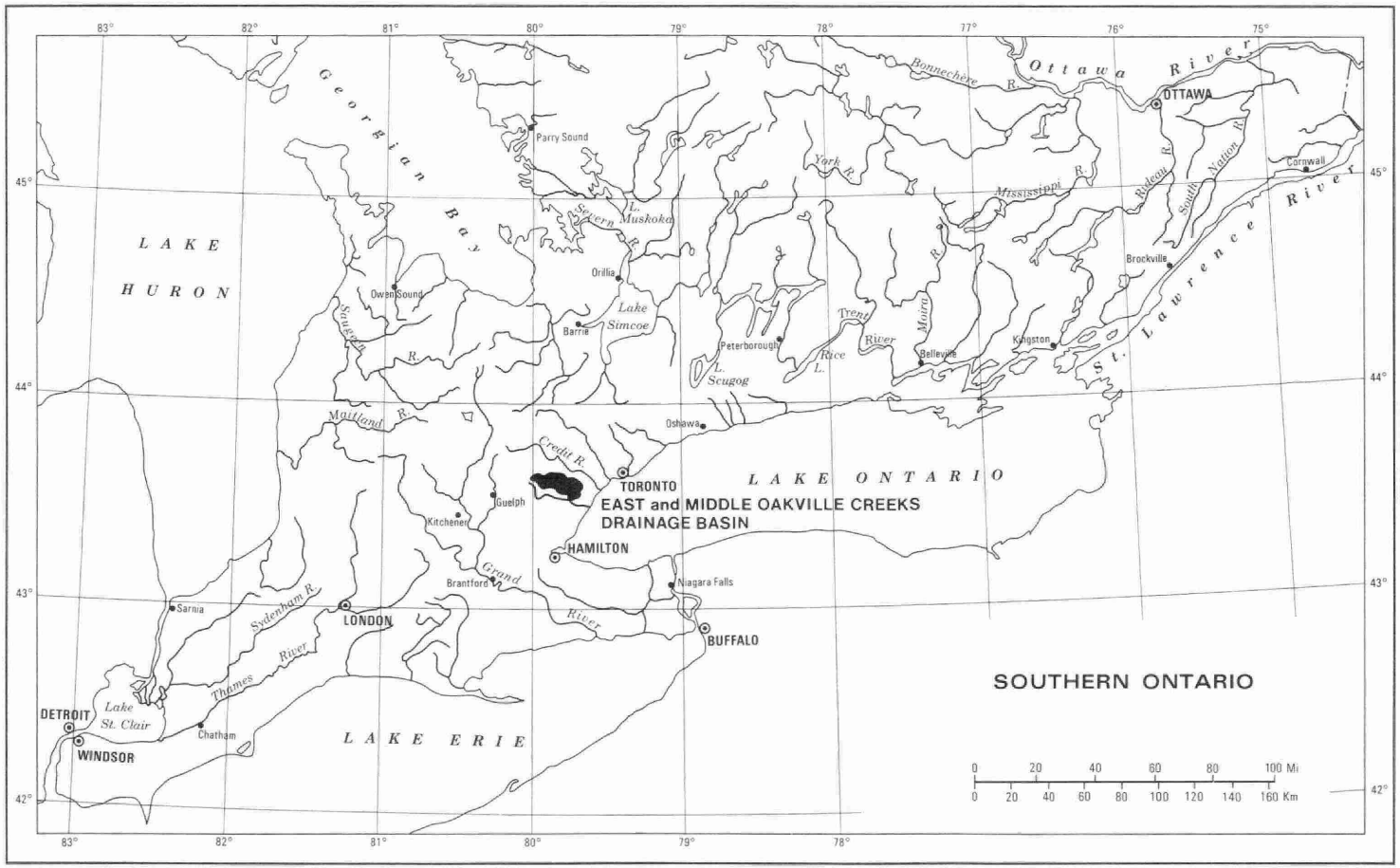

Figure 1. Location of East and Middle Oakville Creeks basin in southern Ontario.

When the single-layer case is not a good approximation of the real situation, or when no coherent patterns are observed in the contours, then strictly quantitative interpretation is not possible and a more qualitative interpretation is accepted which, if necessary, can be supplemented by more detailed investigations at selected sites.

THE EAST AND MIDDLE OAKVILLE CREEKS BASIN RSP SURVEY

In order to test the effectiveness of collinear-dipole RSP combined with VES and seismic refraction studies as a reconnaisance tool for quickly determining the location and distribution of sand and gravel, the method was carried out in 1971 along six traverses about four miles northwest of the Town of Milton, Ontario, in the East and Middle Oakville Creeks Basin (see figures 1 and 2). The first traverse, Section 1, situated about two miles north of the Community of Hornby, was conducted using different dipole widths, in order to find the optimum value for both good resolution and speed of progress. The other five traverses, sections 2 to 6, were selected to represent various typical geological conditions. The ground along these traverses is quite flat, so that topographical effects on the RSP values are small.

GEOLOGY OF THE SURVEY AREA

Lithology and Topography of the Bedrock

The bedrock in the area surveyed is the Queenston Formation of Upper Ordovician age. "The Queenston Formation consists of red mudstone with green siltstone bands; occasionally, green colouring is also present along joints.* The Ordovician shales have a low westward dip and have not, apparently, been tectonically disturbed. However, contortions, folds, and faults can be present ...." (Karrow, 1963). Elevation differences in the bedrock surface, therefore, are most likely of erosional origin. In the area of study, the Queenston Formation is not exposed.

Based on the drillers' logs from water wells, a map of bedrock topography has been compiled as shown in Figure 3. The highest bedrock elevations, over 850 feet, are found along the northern edge of the area studied. The lowest elevations, less than 575 feet, are found in a buried valley in the northeastern portion of the area.

However, some of these depths may not be accurate because "...interpretation of water-well logs is a subject of some uncertainties. Particularly in areas underlain by the Queenston

**Sanford (1961) mentioned that the Queenston Formation consists also of grey crystalline and silty limestone beds, their thickness and number increasing towards the base of the formation.*

Formation, drillers sometimes fail to recognize bedrock until they hit one of the hard siltstone layers; this may be as much as 10 feet below the bedrock surface. In many places, shale grades upwards through a zone of increasingly disturbed material into undisputed till. In other places, several feet of soft weathered shale lie on top of the sounder solid rock ..." (Karrow, 1963).

From the map of bedrock topography, there appear to be several large elongated depressions that are likely buried channels in the bedrock surface. One of these, located just east of the Niagara Escarpment, lies in a north-south direction, passing through Section 6 (figures 2,3). This channel does seem to correlate with the present surface drainage. It likely continues south between Milton Heights and the Escarpment, and also east through Milton, where it follows Oakville Creek toward the southeast. Another channel, roughly 4000 feet south of Middle Oakville Creek near Mansewood, may be traced by following the 625-foot contour. This crosses sections 2, 3, 4 and 5b and appears to be connected with the channel in the northeast portion of the map, continuing toward the southeast and coinciding with the present East Oakville Creek.

Overburden Geology

The overburden thickness varies considerably over the study area and ranges from about 20 feet to approximately 140 feet. The variations are caused mainly by erosional features in the underlying bedrock surface such as buried valleys. Erosional features in the surficial deposits, e.g. stream valleys, cause a thinning of the overburden. Depositional features of glaciofluvial origin such as outwash sands, on the other hand, have often resulted in a thickening of the surficial Pleistocene materials.

The overburden consists mainly of the Halton Till (Karrow, 1963), that is, red and grey clayey or silty till (see Figure 4). Near Section 6 (figures 2 and 4), the Halton Till is overlain by outwash sand. Alluvial deposits and terraces exist along most of the stream courses.

INTERPRETATIONAL PROCESSES

The data from RSP were tied to results obtained from thirteen VES and correlated with the drillers' logs of numerous water wells situated along the sections. In cases where this correlation was not possible, or where the well log information was inconclusive, results from seismic refraction lines were used. Twelve seismic refraction lines (nos. 1 to 12) were conducted during the summer of 1971, and six others (A,E,D, M,N,O) had been conducted previously during the summers of 1969 and 1970.

In the following text, the individual sections are described, using a contoured RSP matrix displayed together with the interpretation of VES, seismic refraction and drillers' logs of water wells. Some correlations of the VES and the refraction seismic results with drillers' logs are shown in more detail in auxiliary diagrams.

The qualitative interpretation of the RSP results in each section is based on the following guidelines:

(1) bedrock shales are assumed to have resistivities of about 80 to 130 ohm-feet,
(2) tills to have resistivities from 100 to 250 ohm-feet,
(3) dirty sands to have values between 200 and 300 ohm-feet, and
(4) clean sands to have resistivities greater than 250 ohm-feet.

In general, the coarser the grain size, the more resistive is the material, and the greater the moisture content, the lower the resistivity. These same guidelines are applied in relating the VES resistivities to type of material.

For the seismic information, the velocity guidelines are:

(1) velocities in the topsoil are generally less than 2000 feet/sec.,
(2) velocities in dry sands and gravels range from 3000 to 4000 feet/sec. depending on compaction,
(3) velocities in water-saturated sands and gravels group near 5000 feet/sec.,
(4) velocities in tills range between 6000 and 8500 feet/sec. and,
(5) velocities in the consolidated bedrock are generally greater than 10,000 feet/sec.

In general, the greater the compaction of a material, the greater is the seismic velocity.

These are only general guidelines, and variations in the values for each type of material can be as much as 10 or even 20 per cent. This inherent ambiguity must be kept in mind when interpreting geology from field measurements of physical properties.

Drillers' logs of water wells are used to calibrate the geological interpretations. While they are generally very useful, some inaccuracies are present, as pointed out by Karrow (1963). One of the most common errors in drillers' logs is the use of the term "clay" to described till. When one sees the term "clay" in a well log, a judgement must be made whether or not the material being described is lacustrine clay or in fact the clay component of a till. In the Oakville Creek Basin, the latter is likely to be true.

GEOPHYSICAL RESULTS

Section 1

Section 1 is situated about two miles north of Hornby and lies in a northwest-southeast direction (Figure 2). Along this section the RSP was done in three separate runs with dipole widths x = 25 feet, x = 50 feet and x = 100 feet, respectively. The dipole widths were chosen so that the theoretical depth of investigation for the fourth depth reading (n = 4) of the 25-foot spacing would be equal to the theoretical depth of investigation for the first depth reading (n = 1) of the 50-foot spacing; similarly, the depth of investigation for the fourth depth reading of the 50-foot spacing would be equal to the first depth reading of the 100-foot spacing. This technique provided an opportunity to compare resistivity values obtained by different dipole widths at the same theoretical depths of investigation. These values for the same theoretical depth of investigation (but for different electrode geometries) should be generally the same, i.e., they should not be different by more than a factor of 1.5.

Two anomalous zones can be observed in the data diagram for dipole width x = 25 feet. From about 350 feet to 500 feet north of the line E (stations 10-14 on the profile with x = 25 feet), higher values of apparent resistivity (250 ohm-feet) are recorded surrounding lower values (around 170 ohm-feet). The other anomalous zone is between distances of 700 and 900 feet north of Line E (stations 26-29, x = 25 feet). Again, higher values on the south side (greater than 210 ohm-feet) and on the north side (greater than 190 ohm-feet) surround a lower resistivity zone (less than 120 ohm-feet).

The first anomalous zone (stations 10-14, x = 25 feet) can be clearly seen only on the smallest dipole width (x = 25 feet) and is not resolved satisfactorily by the x = 100-foot dipole width. It is not readily apparent if the anomaly is caused by lithological change within the overburden or by an undulation in the bedrock surface. Drillers' logs of wells 1354, 1351, 1352 and 1353 indicate a small depression in the shale bedrock overlain by 35 feet of gravels and 5 feet of clay.

The second anomalous zone (stations 26-29, x = 25 feet) can be observed on all three dipole lengths (x = 25, x = 50 and x = 100 feet). This likely indicates an upward undulation of the bedrock surface that is large enough to be resolved by a 100-foot dipole width and is also close enough to the ground surface to be detected by the smallest dipole width. Drillers' logs of wells 1364 and 1346 support this interpretation.

On the basis of the experimental measurements conducted along Section 1, it was decided that for the area in the East and Middle Oakville Creeks Basin, where the overburden thickness varies from 20 to over 400 feet, the dipole widths of x = 100

and x = 200 feet would be used. These larger dipole widths appeared to give sufficient information about the surficial geology and allowed considerably faster progression along traverses.

Section 2

This section is situated along the road between concessions V and VI. Its southeast (SE) end is 2000 feet from Highway 401. The section is 10,000 feet long and extends in the northwest-southeast (NW-SE) direction.

Geophysical investigations included one vertical electrical sounding, ten seismic refraction lines and 10,000 feet of collinear-dipole RSP. Drillers' logs of nineteen water wells situated along the section were available for geological control at the time of study. One of these wells, 0-4b, was logged geophysically, yielding depth profiles of SP, resistance and natural gamma ray activity.

The northern 5300 feet of RSP over the section utilized a dipole width of x = 100 feet and the remaining 4700 feet used x = 200 feet.

Starting from the northern end of the section, the collinear-dipole RSP data indicate a fairly constant lithology on the profiling direction from stations 1 to 25. The corresponding stratified medium consists of a surficial clay layer varying in thickness from 17 to 64 feet, as shown by the drillers' logs of wells 1009 and 1004, respectively. This layer overlies the Queenston shale. In places there are lenses of sand interbedded between the clay and the shale as shown by wells 3509, 3508 and 3465.

The shale bedrock is fairly flat, and dips gently towards the south. Near wells 1002 and 1007, however, a step-like structure is suggested by the drillers' logs of wells 1002, 1007 and 1004, as well as by the results of seismic refraction. An increase in apparent resistivity near stations 14, 15 and 16 may reflect this structure.

South of Station 25, the RSP data indicate a sudden change in pattern associated with a considerable increase in apparent resistivities. This increase is likely due to the lateral change in overburden material as documented by the log of Well 0-4b, which shows 22 feet of clay overlying 46 feet of sand above shale bedrock. The interpretation of VES-10 correlates with the driller's log of Well 0-4b. The boundary at 33.5 feet, not shown in the log of Well 0-4b, is likely the water table. The geological interpretation is corroborated by the results from seismic lines SL-4 and SL-N. The geophysical well logs of Well 0-4b in Diagram A

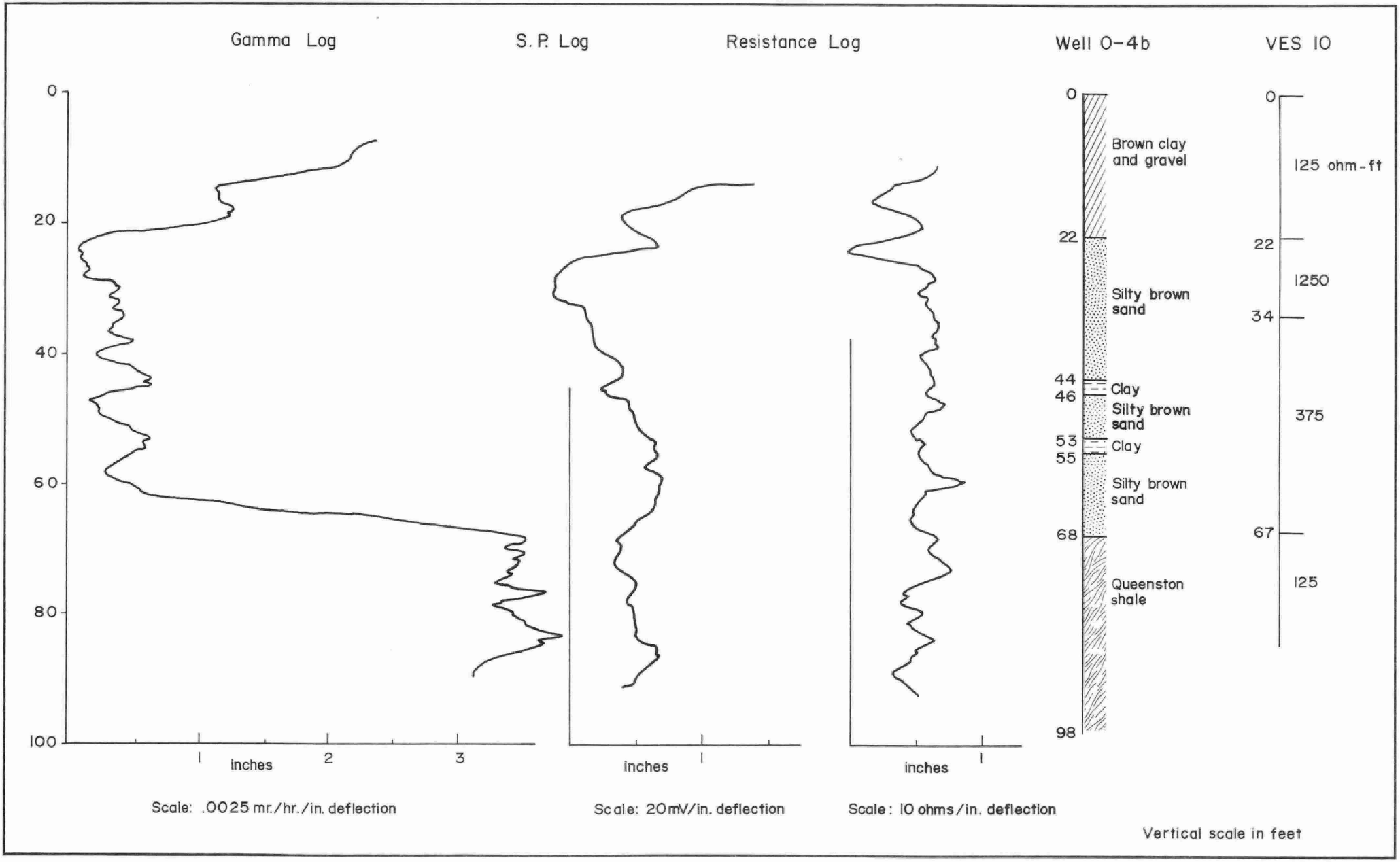
Gamma Log
S. P. Log
Resistance Log
Well O-4b
VES 10
0
20
40
60
80
100
1
2
3
inches
inches
inches
Brown clay and gravel
Silty brown sand
Clay
Silty brown sand
Clay
Silty brown sand
Queenston shale
0
22
44
46
53
55
68
98
125 ohm-ft
1250
375
125
34
67
Scale: .0025 mr./hr./in. deflection
Scale: 20 mV/in. deflection
Scale: 10 ohms/in. deflection
Vertical scale in feet

Diagram A.

display SP (spontaneous potential), single-point resistance and natural gamma ray profiles. The gamma log correlates well with the interpreted sequence of clay (0-22 feet), sand (22-68 feet) and shale. The SP log seems to support the existence of the VES boundary at 33.5 feet, interpreted as the water table.

Towards the south, the sandy material within the overburden remains constant for approximately 1800 feet up to Station 43. South of this station, the observed decrease in resistivities may be explained by the thinning of the layer of sand. This is supported by the driller's log of Well O. W. Sullivan, which indicates only streaks of sand interbedded with clay and till material.

At Well O. W. Sullivan, the bedrock is deeper than 72 feet, while south of Well O. W. Sullivan, it rises gently as shown by the results of SL-10 and the logs of wells 997 and 3097. This rise in bedrock coupled with the absence of significant amounts of sand or gravel is responsible for the decrease in observed resistivities south of Station 43.

At Station 53, the dipole width was increased from 100 to 200 feet and the stations renumbered from 0 up. The rise of the bedrock surface appears to continue south of Well 3097 as indicated by the drillers' logs of wells 993, 991, 996, 994, 995, 990 and 951. Well 3097 penetrates the shale bedrock at a depth of 60 feet as opposed to the 47-foot depth to bedrock at Well 990. This rise is reflected in the RSP data which indicate a gradual decrease in resistivities. This decrease can be traced until Station 21 at the southern end of the section. The rise in the bedrock is also supported by the results of SL-Oa and SL-Ob which show shale velocities about 30 feet beneath the ground surface.

South of Station 21, a lateral change in resistivities is observed. This may be associated with a sudden increase in overburden thickness which is indicated by SL-O and SL-Ob. Results of SL-O and SL-Ob also suggest the existence of a lense of more coarse-grained material, perhaps sandy till which would account for the increase in RSP values.

Section 3

This section is situated 4500 feet southwest (SW) of and parallel to Section 2, along the road between concessions IV and V. The southeast (SE) end of the section is about 500 feet off Highway 401. The section is 10,000 feet long.

Geophysical investigations included two seismic lines, three VES and 10,000 feet of collinear-dipole RSP with a dipole width of 200 feet. Drillers' logs of 14 water wells along the section provided geological control.

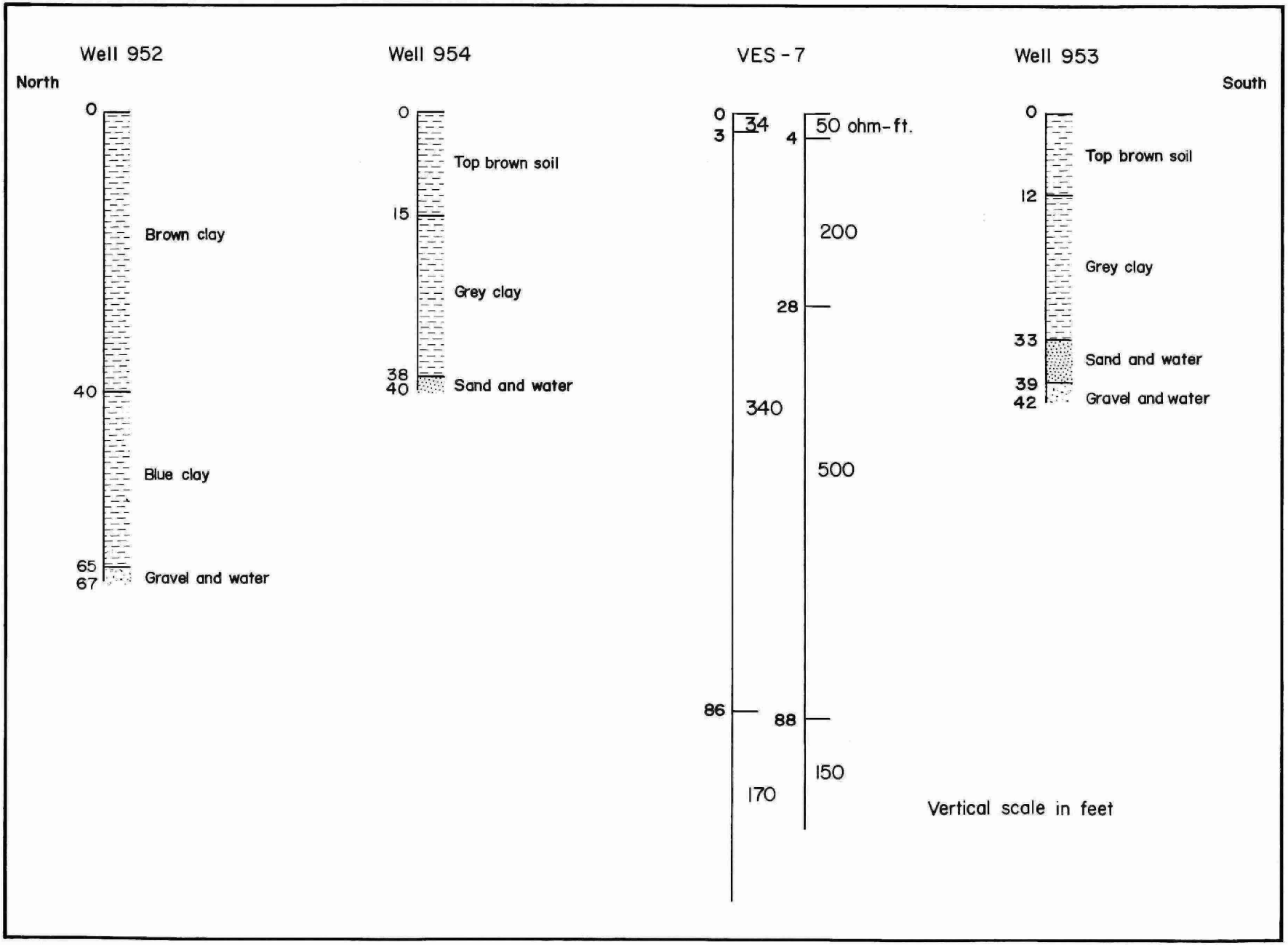
Well 952
North
0
Brown clay
40
Blue clay
65
67
Gravel and water
Well 954
0
Top brown soil
15
Grey clay
38
40
Sand and water
VES - 7
0
3
34
50 ohm-ft.
4
200
28
340
500
86
88
150
170
Well 953
South
0
Top brown soil
12
Grey clay
33
Sand and water
39
42
Gravel and water
Vertical scale in feet

Diagram B .

From Station 1 to Station 8, the RSP resistivity values are consistent with the geology suggested by the log of Well 957. From Station 8 to Station 10, the RSP resistivities show a resistive deposit with resistivities of about 250 ohm-feet. The existence of this deposit is supported by VES-5. A small layer of gravel is indicated at depth in this area by wells 891 and 886. If this layer thickens towards Well 886, it could account for the RSP resistivity anomaly. Alternatively, the anomaly may be due to a dry sandy till.

Between stations 13 and 16, a disturbance in the resistivity pattern is observed. This is accompanied by a resistive (338 ohm-feet) layer shown by VES-6. The cause for these observations is likely the localized occurrence of a dry sandy till.

The bedrock gently slopes downward from 35 feet at the north end of SL-E to 43 feet at the south end, and to about 56 feet at VES-6. The downward slope continues to Station 24, where VES-7 shows a likely bedrock depth of about 88 feet. The interpretation of VES-7 is ambiguous (see Diagram B), showing two possible sequences of resistivities for the overburden materials.

A bedrock depression appears to be centred near wells 952 and 954. The resultant thickening of the overburden in this area, with possibly an increase in coarse-grained material, is reflected by the RSP data which have values of over 300 ohm-feet. South of Station 24, the bedrock likely rises again, resulting in the thinning of the more resistive overburden. Thus, the RSP values begin to fall. An apparent resistivity anomaly in the RSP data occurs at Station 34. However, it is not due to geological effects, but is a result of interference from the Bell Telephone Cable which is suspended about 20 feet above the ground surface.

South of Station 36, the RSP results correlate with drillers' logs of wells 880, 2967, 950, 879, 2971, 877, 876 and 875, indicating that the overburden thickness is gradually decreasing toward the south. The depth to bedrock is 68 feet in Well 880, and only 22 feet in Well 875, 2,000 feet to the south.

The major feature of note along this section is the bedrock depression centred about Station 22. Collinear-dipole RSP information alone seems able to discern the existence of this depression. If the fill material had been more resistive, the resistivity data would be much more diagnostic for the depression.

Section 4

This section is 10,000 feet long and parallels sections 2 and 3. It lies along the road between concessions III and IV. On the section are 11 wells from which information on the subsurface geology was derived. The RSP survey was supplemented by one seismic line and two vertical soundings.

From Station -5 south to Station 16, the RSP resistivity values are generally low and stable. This observation is consistent with the drillers' logs of wells 2979, 893, 810, 3464 and 3429, and the interpretation of VES-2, which show a fairly conductive overburden of clay and till with streaks of sand and gravel. Bedrock depths, extrapolated north from seismic line SL-11 on Section 5b, are likely to be approximately 45 feet (see Base Map and Figure 3).

South of Station 16 to Station 29, a broad, resistive feature appears on the RSP data. According to SL-9, the bedrock has deepened to about 100 feet. This depth likely increases toward the south according to the interpretation of VES-3 which shows shale (resistivity of 80 ohm-feet) at a depth of 108 feet. Well 805 shows that bedrock is shallower (66 feet) south of Station 28. Thus, a broad depression can be associated with the RSP resistive feature, centered about stations 24 to 28. The depression in the bedrock is likely filled with a material with a high component of sand (wells 2740, 809, 889 and VES-3), accounting for the higher RSP resistivities. Unfortunately, well data are not available over the centre of the resistivity anomaly to support this conclusion.

At Station 31, an outstanding anomaly occurs in the RSP contour map. As in Section 3, this anomaly is associated with a Bell Telephone main line hanging about 20 feet overhead.

South of Station 34, the disturbance on the RSP data due to the telephone cable has diminished. From Station 34 to Station 44 at the southern end of the section, the RSP contours are fairly stable. A single feature of note is located at Station 35, where a resistivity of over 300 ohm-feet is observed. VES-4 also shows a resistive overburden. However, wells 3287 and 878 show only clay and till in the overburden; thus it is likely that the electrical information reflects only an isolated pocket of resistive, coarse-grained material, or that the electrical resistivity values have been increased by a decrease in moisture content in the overburden. Depth to bedrock seems to vary south of Station 29 from 66-41 to 60-73 feet (wells 805, 3287, VES-4 and Well 878).

As in Section 3, the main feature shown by RSP data in Section 4 is a depression filled with resistive material. The resistivity anomaly (centred near stations 23 to 28) associated with the resistive fill is quite strong. These features shown on both sections 3 and 4 are probably due to the same depression in the bedrock.

Sections 5a, 5b

The locations of sections 5a and 5b are shown on the Base Map. Section 5a is the eastern portion of the profile,

while Section 5b is the western portion. Altogether, there are eight water wells along the sections, and geophysical investigations included five seismic lines, two VES surveys and 10,000 feet of RSP with a dipole width of 200 feet.

At the eastern end of Section 5a, wells 1014 and 1009 show bedrock at a depth of less than 20 feet, while near Station 4, well 3509 indicates that the underlying shale is more than 44 feet deep. West to Station 8, the bedrock is found by the results of SL-D to be at 62 to 86 feet. This increase in bedrock depth from Station 1 to Station 8 does not seem to affect the RSP data, with resistivity values being fairly constant laterally. It is likely that the overburden resistivity is close to that of the underlying shale in this portion of the section.

At Station 9, the RSP data reveal a resistive anomaly at depth. VES-8 also suggests the existence of a more resistive deposit at depth. As there is no well information to confirm the electrical data, there is some ambiguity as to whether or not the resistivity anomaly is due to lateral changes in the surficial deposits or to an actual deposit of coarse-grained material at depth.

From Station 10 to Station 13, the RSP data exhibit no drastic variations in the resistivity patterns. Seismic line SL-6 shows bedrock at a depth of 123 feet to 117 feet. This does not agree well with the bedrock depth of 93 feet indicated by Well 956. However, Well 956 shows that a layer of sand lying between the surficial till and the bedrock likely results in a seismic velocity inversion. This sand layer, whose existence is supported by the evidence from VES-9, results in a calculated seismic bedrock depth greater than the true depth. A correction for the depth to bedrock to account for the velocity inversion may be in the order of 10 to 20 feet.

From Station 13 to Station 17, the RSP data seem to indicate an increase in overburden thickness and a slight decrease in overburden resistivity. An increase in overburden thickness is likely, as SL-7 does not record any arrivals from the bedrock, indicating that it is deeper than usual. Alternatively, the bedrock surface may be so complicated that arrivals from it are scattered and thus unrecorded. The decrease in RSP resistivity may be due to pinching out of the sand layer shown in the driller's log of Well 956.

In the portion west of Station 17 to the end of the section, there is a fairly large RSP anomaly at stations 18, 19 and 20. The only well available here, Well 892, shows no resistive,

coarse-grain materials. However, the till shown by Well 892 may be more gravelly than usual, accounting for the increase in RSP values. The bedrock surface has risen to depths of 78 to 50 feet (SL-M and Well 892), and the seismic data indicate the disappearance of the relatively high velocity layer (greater than 7000 feet/ sec) shown by SL-D and SL-6. The RSP data alone reflect these complicated changes, although there would be much difficulty in deciding what caused the RSP variations if additional information were not available.

The RSP contour map for Section 5b is a very stable one. There are only two features worthy of note. The first, at Station 3, may be due to a local deposit of sand or gravel on the surface. The second, between stations 13 and 14, is due to the CPR tracks. The resistivity values on the contour map indicate that the overburden for this section consists mostly of till with some dirty sand.

There are only three wells on the section. Wells 890 and 881 on the eastern end of the section show a mixture of sand and clay overlying the shale bedrock at 69 to 52 feet.

The depth to bedrock of 52 feet shown by Well 881 is confirmed by the seismic depths of 51 and 44 feet (SL-11). Well 3359 near Station 18 is too shallow to show bedrock. By extrapolating the geology shown by wells 890 and 881 on the basis of the RSP data, the conclusion can be drawn that the overburden along Section 5b has a fairly uniform thickness (between 70 and 40 feet), with only a small component of resistive sands in the clay and till.

Section 6

Section 6 lies 10,000 feet northwest and parallel to Section 5 (see Base Map). The geophysical investigations here included about 9,000 feet of RSP using a dipole width of 200 feet, one VES and one seismic line. Nine wells along the section provided geological calibration for the geophysics.

From Station 0 to Station 9, the RSP resistivities indicate mixtures of sand and clay in the overburden. The deep RSP values are typical of the shale bedrock. The log of Well 897 is consistent with the RSP.

Between Station 9 and Station 22, the RSP resistivities attain high values, indicating that the bedrock has deepened and that the composition of the overburden has become more coarse-grained. Consistent with the RSP resistivities, wells 896, 894 and 895 show a larger component of sand. Interpretation of the RSP data suggests that the sand indicated at the

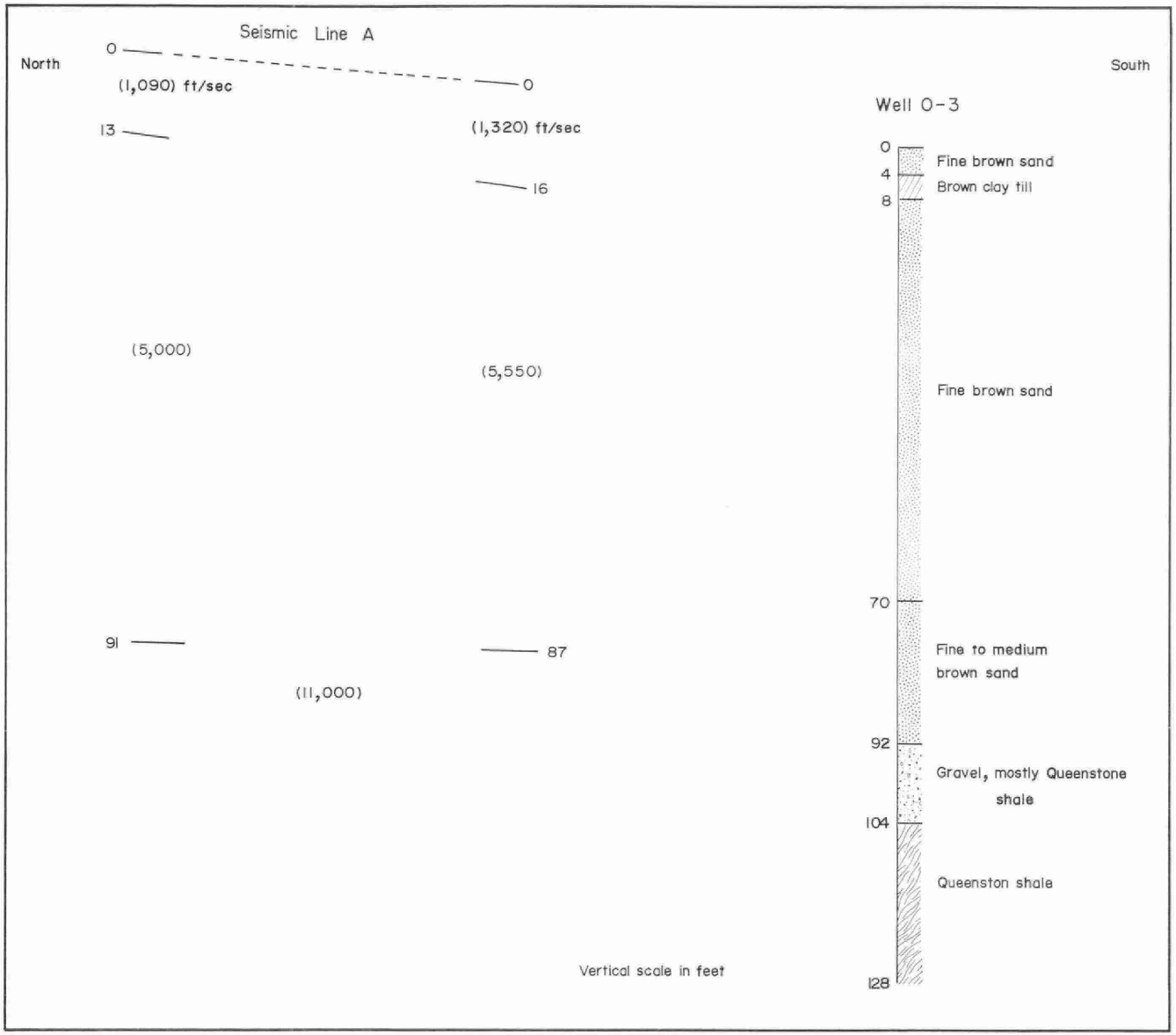
Seismic Line A
North
South
0
0
(1,090) ft/sec
(1,320) ft/sec
13
16
(5,000)
(5,550)
91
87
(11,000)
Vertical scale in feet
Well O-3
0
4
8
70
92
104
128
Fine brown sand
Brown clay till
Fine brown sand
Fine to medium brown sand
Gravel, mostly Queenstone shale
Queenston shale

Diagram C.

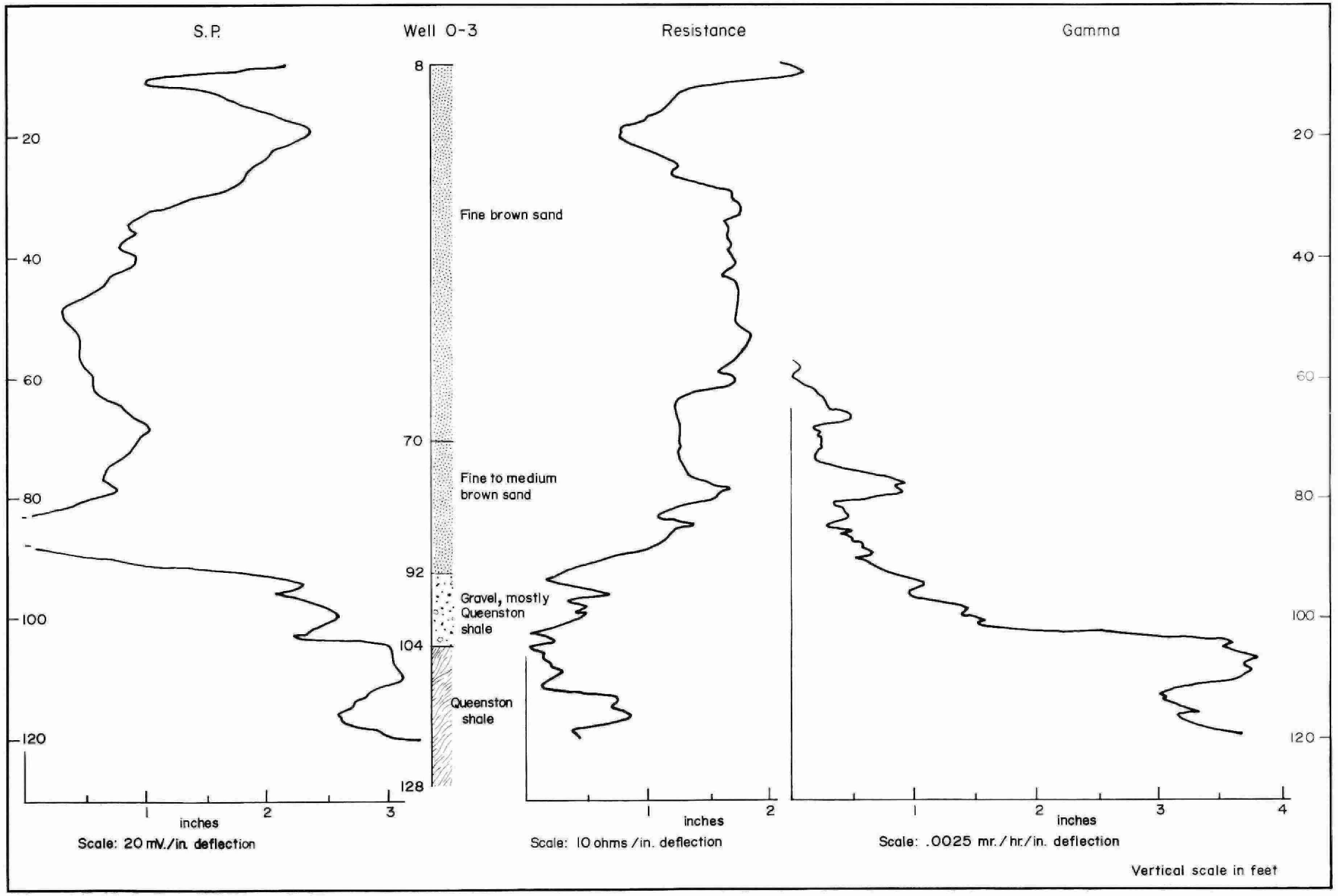
S.P.
Well O-3
Resistance
Gamma
20
40
60
80
100
120
8
70
92
104
128
Fine brown sand
Fine to medium brown sand
Gravel, mostly Queenston shale
Queenston shale
1
2
3
inches
Scale: 20 mV./in. deflection
1
2
inches
Scale: 10 ohms /in. deflection
1
2
3
4
inches
Scale: .0025 mr./hr./in. deflection
Vertical scale in feet

Diagram D.

bottom of Well 896 is likely to be fairly thick; that is, the bedrock is greater than 102 feet deep. Seismic line SL-8 shows that bedrock velocities are reached at 140 to 134 feet; however, because of the possibility of velocity inversions, it may be necessary to revise these depths upwards.

Between Station 22 and Station 29, the RSP resistivities have again decreased to values typical of dry sandy tills. Values at depth indicate that bedrock is likely to be found at the depths suggested by SL-8.

Between Station 29 and Station 33, the RSP show a near-surface anomaly. However, its limited size and coincidental occurrence with the railway tracks make the origin for it likely to be disturbance by the tracks. RSP resistivities at depth show that bedrock has risen, and SL-A (located near Well 0-3 but not shown on the section; see Base Map) and the log of Well 0-3 indicate shale at depths of 91, 87 and 92 feet (see Diagram C). The near-surface RSP values are generally those expected for dirty sand.

Geophysical well logging was done in Well 0-3. The results are presented in Diagram D. Both the SP and resistance logs indicate variations in the dirtiness of the sand in the upper 90 feet of the well. The SP reflects very strongly the interface at 92 feet between the medium sand and the gravelly shale, while the gamma log picks up the shale bedrock boundary at 104 feet.

From Station 33 to Station 39, RSP values are relatively higher and typical of cleaner and thicker layers of sand, with the possibility of some gravel. Wells 828 and 822 show thick layers of sand, and bedrock appears to be below 140 feet. VES-1 also shows a very resistive layer, underlain by a more conductive layer. This conductive layer is probably responsible for the lower RSP values at depth and might be due to the saturation by water of the sands. From Station 39 to the end of the section, the RSP values become lower. The resistivities observed are those associated with dry tills and mixtures of clays and sands. The drillers' logs of wells 824 and 826 agree with the RSP observations. From these observations, it appears that near Station 39, a change from highly resistive material (clean sands) to moderately resistive material (dirty sands) occurs in the overburden. The bedrock remains quite deep (greater than 145 feet in Well 824).

CONCLUSIONS AND RECOMMENDATIONS

The investigations carried out in the East and Middle Oakville Creeks Basin have shown that the RSP method using the collinear-dipole array in certain geological situations is an effective and relatively inexpensive exploration tool giving reliable information on the location and distribution of subsurface sands and gravels. The technique is most effective when the sands and gravels have higher resistivities than the background geology, as is the case in the East and Middle Oakville Creeks Basin.

Based on the experience gained in the experimental project carried out in this area, the following procedure is recommended for applying the electrical techniques for finding sand and gravel deposits where a generally conductive background exists against which the resistive,coarse-grained deposits are contrasted.

(1) A topography map of the bedrock surface (if any) should be compiled to delineate depressions or buried valleys which may contain outwash sands and gravels.

(2) The collinear-dipole RSP method should be conducted to obtain a resistivity profile or map of all areas likely to contain deposits of coarse-grained material.

(3) Qualitative interpretation of the RSP data should be done to determine the sites most likely to yield sand and gravel. This involves calibrating the measured resistivities against the real geology with the assistance of available water-well or drilling information.

(4) Where necessary, refinement of the geophysical information and interpretation should be done using VES methods, seismic refraction and well logging.

(5) The likeliest sites should be examined by drilling.

The key to the economical prospecting for coarse-grained deposits as outlined in the above procedure, is the ease and speed of the collinear-dipole RSP technique as a reliable ground reconnaissance tool.

PART II

SEISMIC REFRACTION INVESTIGATIONS IN SUPPORT OF A GROUND WATER SURVEY NEAR THE VILLAGE OF ALFRED

Figure 5. Location of cross-sections and water wells near Alfred.

SEISMIC REFRACTION INVESTIGATIONS IN SUPPORT OF A GROUND WATER SURVEY NEAR THE VILLAGE OF ALFRED

INTRODUCTION

At the request of the former Surveys and Projects Section of the Water Quantity Management Branch, a geophysical survey was conducted near the Village of Alfred during the month of July, 1972. The geophysical survey was designed to obtain information on the depths and topography of the bedrock surface and on the materials within the overburden. The survey, consisting of 18 seismic refraction lines supplemented by one vertical electrical sounding (VES) and logging of test well TW-1, was carried out in the area shown in Figure 5.

GEOLOGY OF THE AREA

Bedrock

The bedrock underlying the area of investigation is mapped as the Ottawa Formation of Ordovician age and consists of limestone of the Rockland beds in the southern portion of the area, limestone of the Leroy beds and chiefly shaly limestone of the Lowville beds in the central portion, and limestone, dolomite, shale and thinly-bedded sandstone of the Pamelia beds in the northern portion. The bedrock outcrops locally along a prominent bedrock ridge, trending east-west, located about one mile north of the Village. The shaly limestone of the Lowville beds is exposed in a road-cut and also in an abandoned quarry, both about 1.3 miles north of the Village. The formation appears to dip to the southwest at about nine degrees. From published descriptions of the Ottawa Formation, there appear to be lithological changes from the shaly limestone of the Lowville beds to denser limestones of the younger Leroy beds and Rockland beds. The younger formations form the bedrock surface south of the ridge. The bedrock topography is gently undulating while sloping down away from the ridge. A high degree of weathering and many fractures can be observed near the top surface of the bedrock in the above-mentioned road-cut. It is assumed that weathering of the bedrock would be more intense toward the ridge and also that the density of fractures would increase as the bedrock nears the ground surface.

Extensive regional faulting is present in the bedrock of the Ottawa valley and two major faults extending in an east-west direction, approximately parallel with each other, are mapped in the immediate area. One is located on the north side of the aforementioned bedrock ridge about one-half mile north of seismic line S-15; the other is located south of of the Village and appears to extend between wells 9 and 13 (Figure 5).

Overburden

The overburden in the area of investigation consists generally of sand of fluvio-lacustrine origin, silt and clay of marine origin and deeper sands and gravels probably of fluvial origin. The silt and clay appear to be deposited throughout the entire area of investigation and form by far the thickest formation. Test wells TW-1 and TW-2 indicate the thickness of the clay formation to be 53 and over 60 feet, respectively (Figure 6). This formation appears to be underlain by sands and gravels of varying thickness, deposited directly on the bedrock surface (see Figure 6 for the geological logs of wells 6, TW-1 and TW-2). The clay formation in the area is either exposed at the surface or overlain by deltaic deposits of fine-to-medium-grained sand formed during the early stages of the present-day Ottawa River. Erosion of the delta by the river during the post-glacial uplift of the region has caused the exposure of the marine clay (silt) deposits in some places between isolated sandy plains and ridges.

GEOPHYSICAL INTERPRETATION

Bedrock

The slope of the bedrock surface appears to be steeper on the north side of the ridge than on the south side of the ridge (see figures 6, 9, 10 and 12). This statement is supported by the data obtained from all seismic lines perpendicular to the ridge. Seismic lines S-14 and S-15 (Figure 13) on the north side of the ridge also indicate that the surface of the bedrock tends to level off at about 1,500 feet north of the ridge.

An increase is observed in the velocity of the compressional seismic wave from the bedrock, from the ridge southward in a direction approximately perpendicular to the ridge. The bedrock velocity near the ridge, where the depth to the bedrock is shallow, is recorded to be about 16,400 feet/sec (under seismic line S-1, Figure 6); further south under seismic line S-5, by test wells TW-1 and TW-2, it is about 19,100 feet/sec; and approximately a half-mile south of the ridge under seismic line S-5, where the depth to the bedrock appears to be greatest, it is about 19,200 feet/sec. Bedrock velocities recorded on seismic refraction lines S-3, S-7, S-2 and S-4 situated approximately in an east-west direction parallel to the ridge (Figure 5) range from 17,000 to 17,700 feet/sec.

Both weathering and fractures in the bedrock may be at least partly responsible for the velocity anisotropy in the different directions. In addition, lithological changes from the shaly limestone of the Lowville beds into the younger

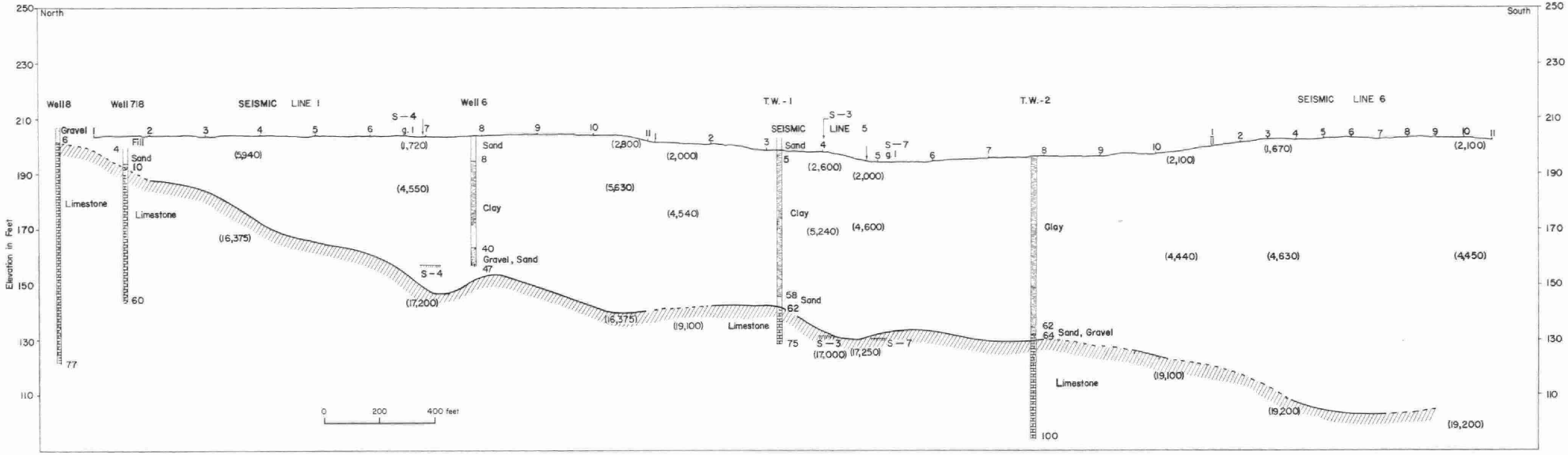

Figure 6. Cross-section 1, N-S.

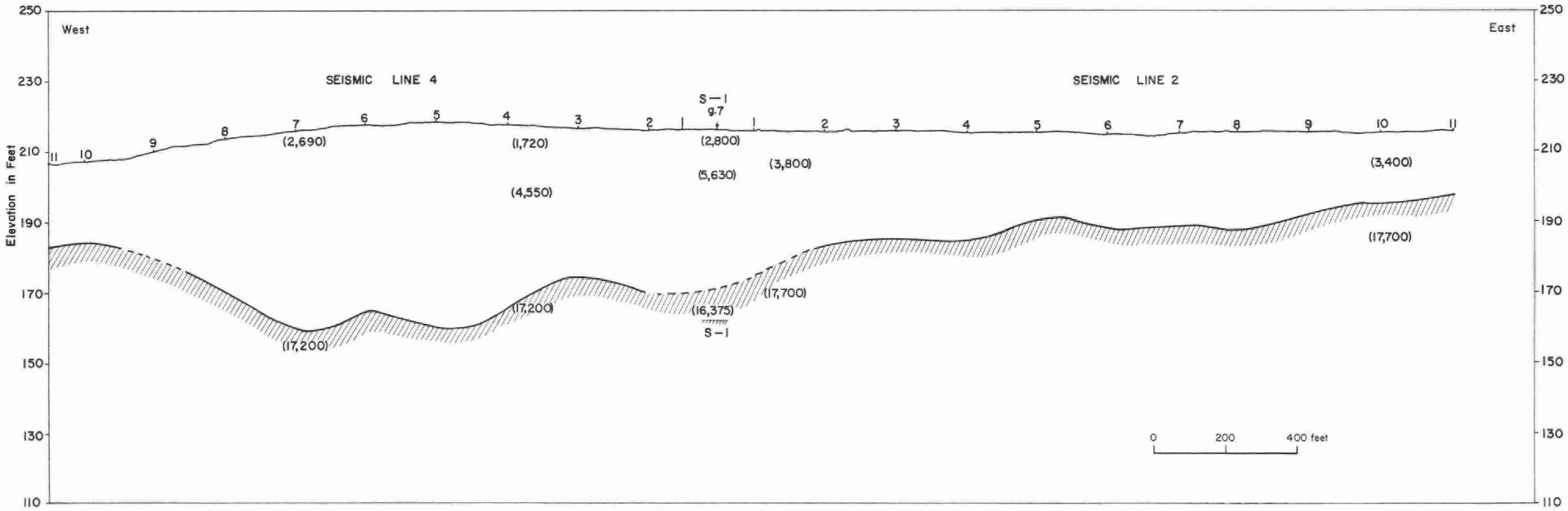

Figure 7. Cross-section 2, W-E

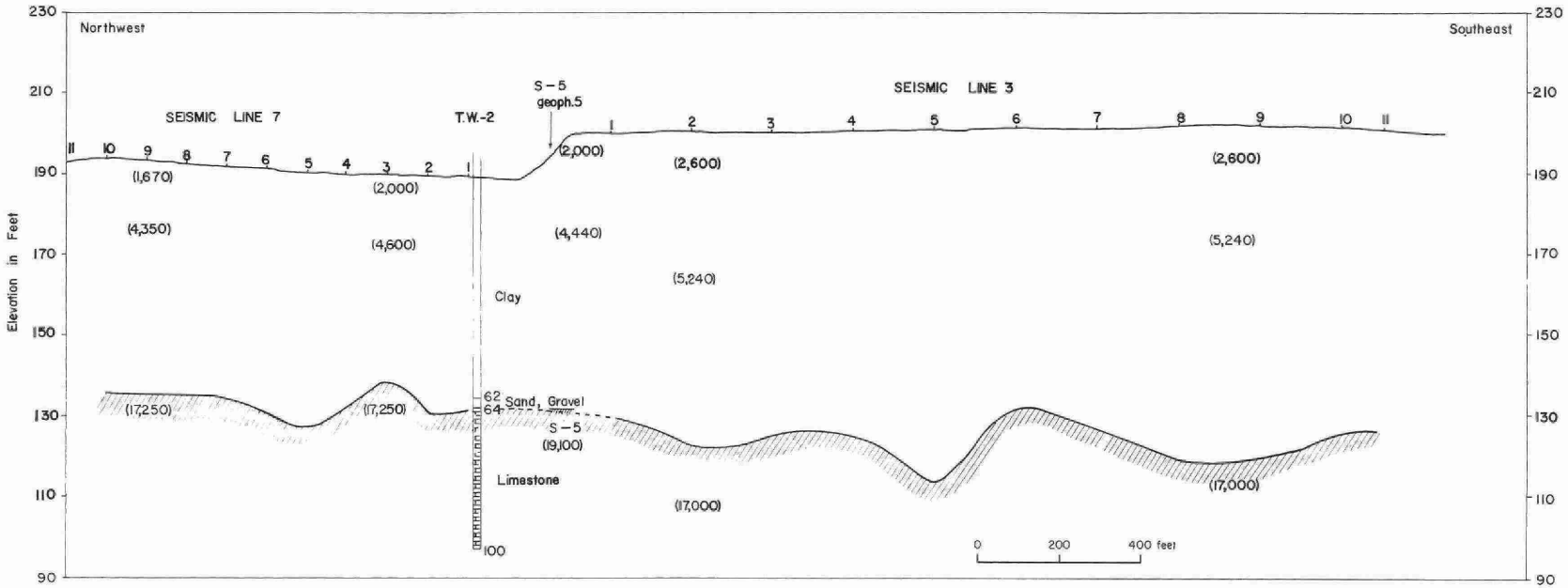

Figure 8. Cross-section 3, NW-SE.

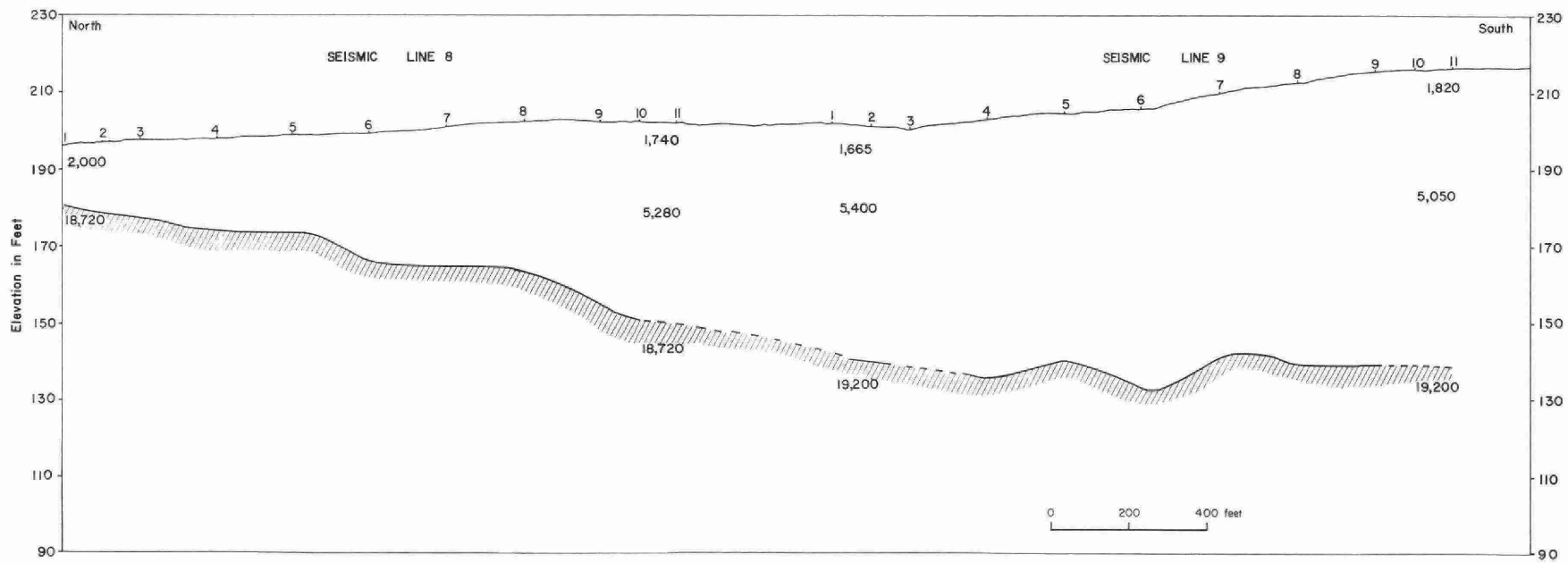

Figure 9. Cross-section 4, N-S.

and denser limestone of the Leroy beds and further into the limestone of the Rockland beds may also be responsible for the velocity increase toward the south.

Generally, higher velocities ranging from 18,200 to 20,000 feet/sec are recorded in the western portion of the area, under seismic lines S-8, S-9, S-10, S-11, S-12 and S-13 (figures 5, 9, 10 and 11). Again, lower velocities are recorded closer to the ridge and higher velocities further from the ridge in the north-south direction; however, there is no evidence for a velocity anisotropy phenomenon as observed in the eastern portion. Possibly the slope of the bedrock which appears to be gentler in the eastern portion and a difference in the degree of fracturing and weathering may account for the absence of the anisotropy.

The map of bedrock topography based on interpretation of geophysical data is shown in Figure 15.

A different bedrock velocity situation is recorded on the opposite (north) side of the ridge under seismic lines S-14 and S-15, where the velocity appears to remain horizontally constant. The velocity of 15,400 feet/sec recorded under both seismic lines S-14 and S-15 (Figure 13) does not appear to be representative of the material indicated by velocities on the south side of the ridge. It appears that either a facies change (increased shaly component in the limestone of the lowermost Lowville beds) or a lithological change into underlying Pamelia beds is responsible for the lower velocity.

Overburden

Two ranges of velocities are generally recorded within the overburden. A lower velocity range (from about 1,600 to 2,600 feet/sec) is recorded for the uppermost unsaturated material, the thickness of which appears to vary from five to 17 feet. Any velocity variation in this material may be caused by lateral changes in its composition (sand, silt or clay) or in its moisture content, or both.

A higher velocity range (from about 4,350 to 6,350 feet/sec) corresponds to the marine clay and/or silt beneath the uppermost layer. Lateral velocity variations within this formation are recorded under many seismic lines (see figures 6, 8, 10, 11 and 13) and these may be due to facies changes and/or to sloping interfaces.

The water-saturated sands and gravels reported from some wells in the area of investigation (wells 6, TW-1 and TW-2; Figure 6) are expected to exhibit a similar velocity to that of the overlying clay. Thus, water-saturated sands and gravels would not be distinguishable from the clays on the basis of seismic data only.

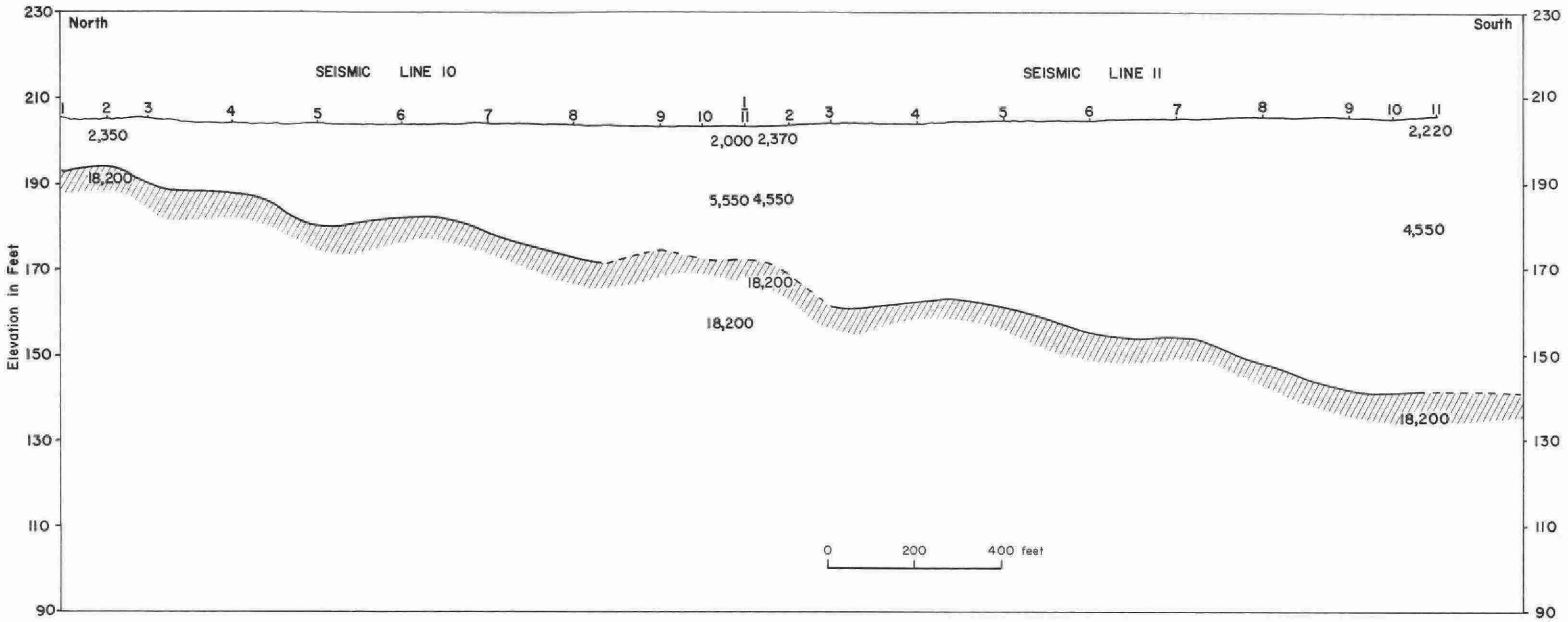

Figure 10. Cross-section 5, N–S.

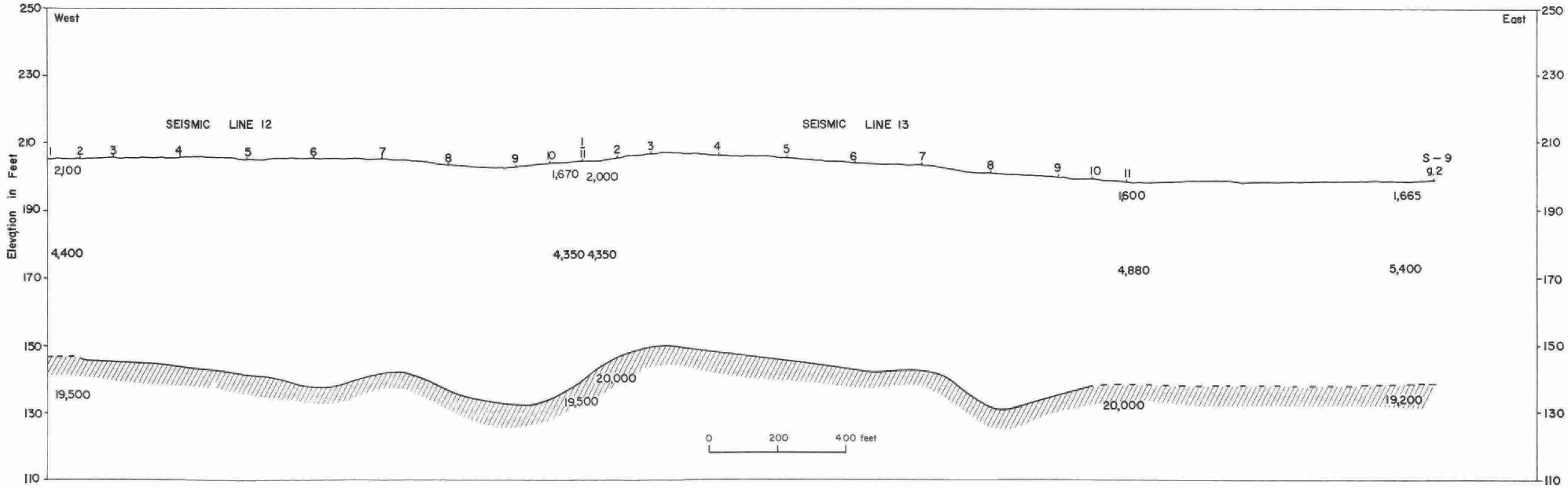

Figure 11. Cross-section 6, W–E.

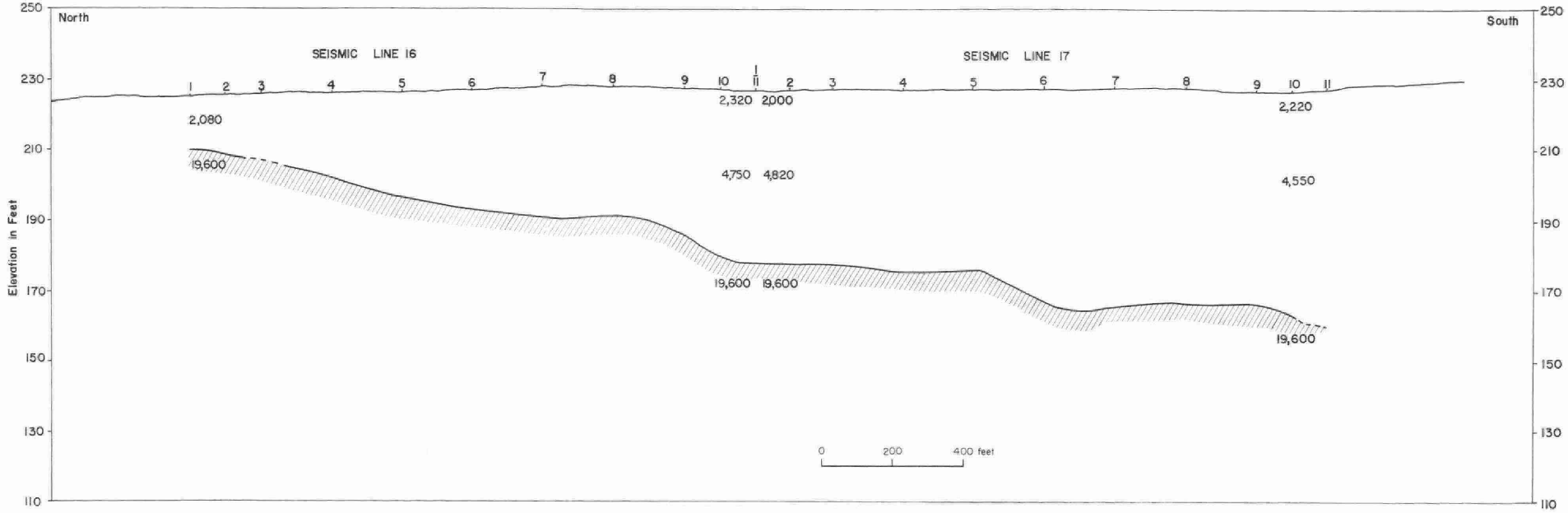

Figure 12. Cross-section 7, N-S.

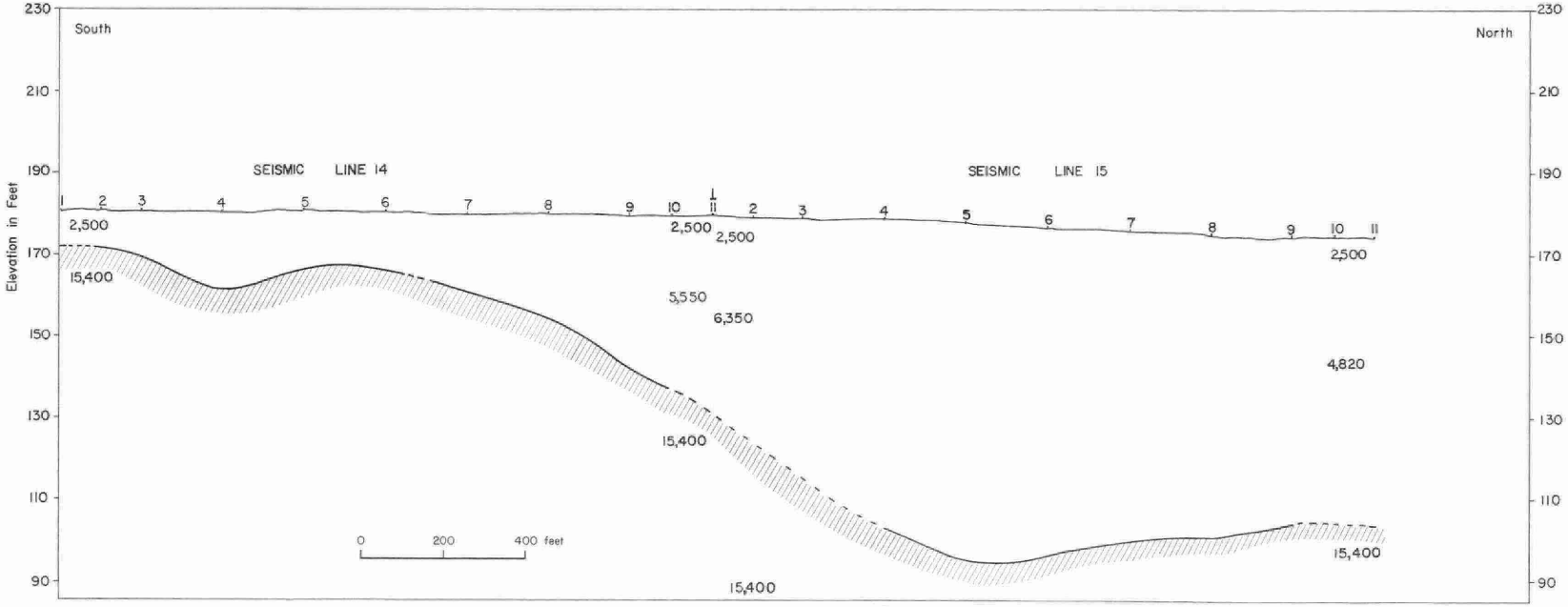

Figure 13. Cross-section 8, S - N

In an attempt to detect the sands and gravels deposited on top of the bedrock, the use of electrical resistivity methods was considered. The success of using electrical methods in this area would depend on the resistivity contrasts of the sands and gravels with both overlying clay and underlying limestone. Also, the resistivity of water-saturated sands and gravels depends on the chemical composition of the water, mainly on its salt content. If the sands and gravels were saturated with fresh water, some resistivity contrast with the overlying clay and no or small resistivity contrast with the underlying limestone would be expected; therefore, it would appear that the sands and gravels-limestone interface would not be detectable. The sands and gravels-clay interface could not be distinguished from the clay-limestone interface by means of the resistivity method alone, in the case where sands and gravels were not deposited on top of the bedrock. Therefore, the sands and gravels-clay interface would be detected only by correlation with the seismic method or other information (e.g. a well).

In the case of sands and gravels containing salty water, small or no resistivity contrast would be expected with the overlying clay but some resistivity contrast would be expected with the underlying limestone (both depending on the concentration of salt in the water). The sands and gravels-clay interface could not be detected because of a lack of resistivity contrast. The sands and gravels-limestone interface could probably be detected; however, it could not be distinguished from a clay-limestone interface.

To overcome the above-mentioned difficulties, an electrical log of test well TW-1 was contemplated. Such a log would be essential to allow for formation correlation for vertical electrical sounding (VES). Unfortunately, an electric log could not be obtained from the well because of the hole being cased for almost its entire depth. The caliper, natural gamma-ray and temperature logs of test well TW-1 are shown together with the geological log in Figure 14.

VES-1 was conducted at the west end of seismic line S-4 (Figure 5) where it was anticipated that any sands and gravels present would be saturated with fresh water. As expected, a depth to the sands and gravels-limestone interface could not be uniquely obtained from resistivity data alone. The lowest interface interpreted from VES-1 appears to be at depths ranging from 14 to 22 feet. The results obtained from seismic line S-4 suggest depths of about 23 feet to bedrock on the west side of the line. Distortion of the resistivity data from VES-1 may have occurred due to sloping interfaces and this distortion may be severe; therefore, no unambiguous interpretation could be obtained

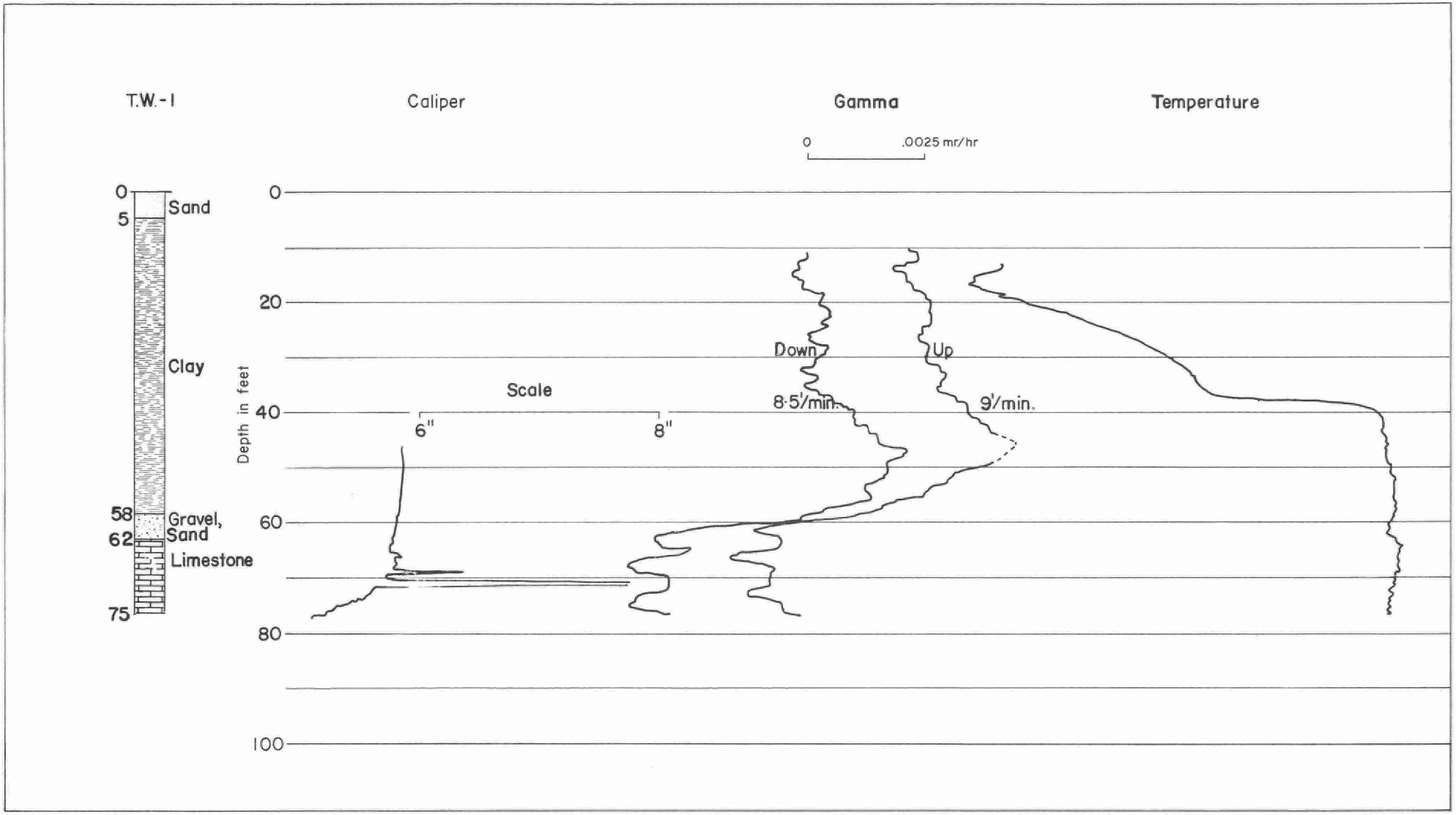

Figure 14. Composite log of Test Well 1.

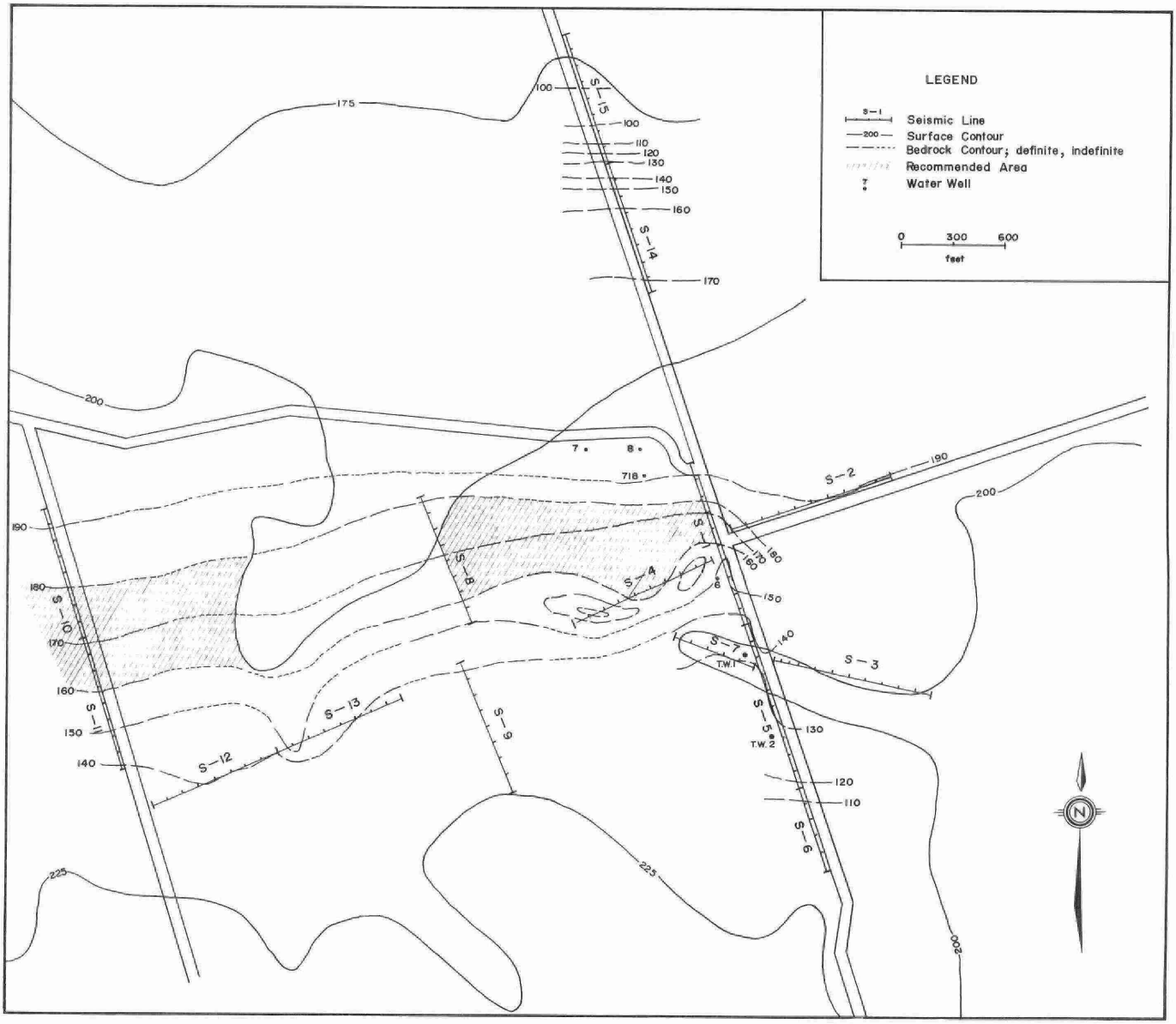

Figure 15. Bedrock topography.

using the combined seismic and resistivity correlations. Further attempts with VES methods were not considered for this area.

CONCLUSIONS AND RECOMMENDATIONS

From the geophysical survey, depths to the bedrock, and slope and topography of the bedrock surface were obtained on both the south and north side of the ridge. The degree of weathering and density of fractures together with some lithological changes in the bedrock may explain the observed velocity anisotropy. These findings have been used in the location of suggested test sites.

It appears from well logs of wells 6, TW-1 and TW-2 (Figure 6) that the sands and gravels deposited on top of sloping bedrock close to the ridge have more probability of being fresh-water saturated than those deposited further from the ridge and/or on the flat-lying bedrock.

Based on the interpretation of geophysical and geological data, it was recommended that test-drilling sites be selected as far south of the ridge as possible (quantity) but in the area where the slope of bedrock is still relatively steep (quality). The area recommended for test drilling is shown on the map of bedrock topography (Figure 15).

Test drilling was not carried out because other hydrogeological investigations (Andrijiw, 1973) indicated that any water from the survey area would likely not meet quality standards due to high chloride concentrations.

PART III

RESISTIVITY INVESTIGATIONS OF THE SALT-WATER CONTAMINATION OF A SANDY AQUIFER IN THE TOWNSHIP OF ANCASTER

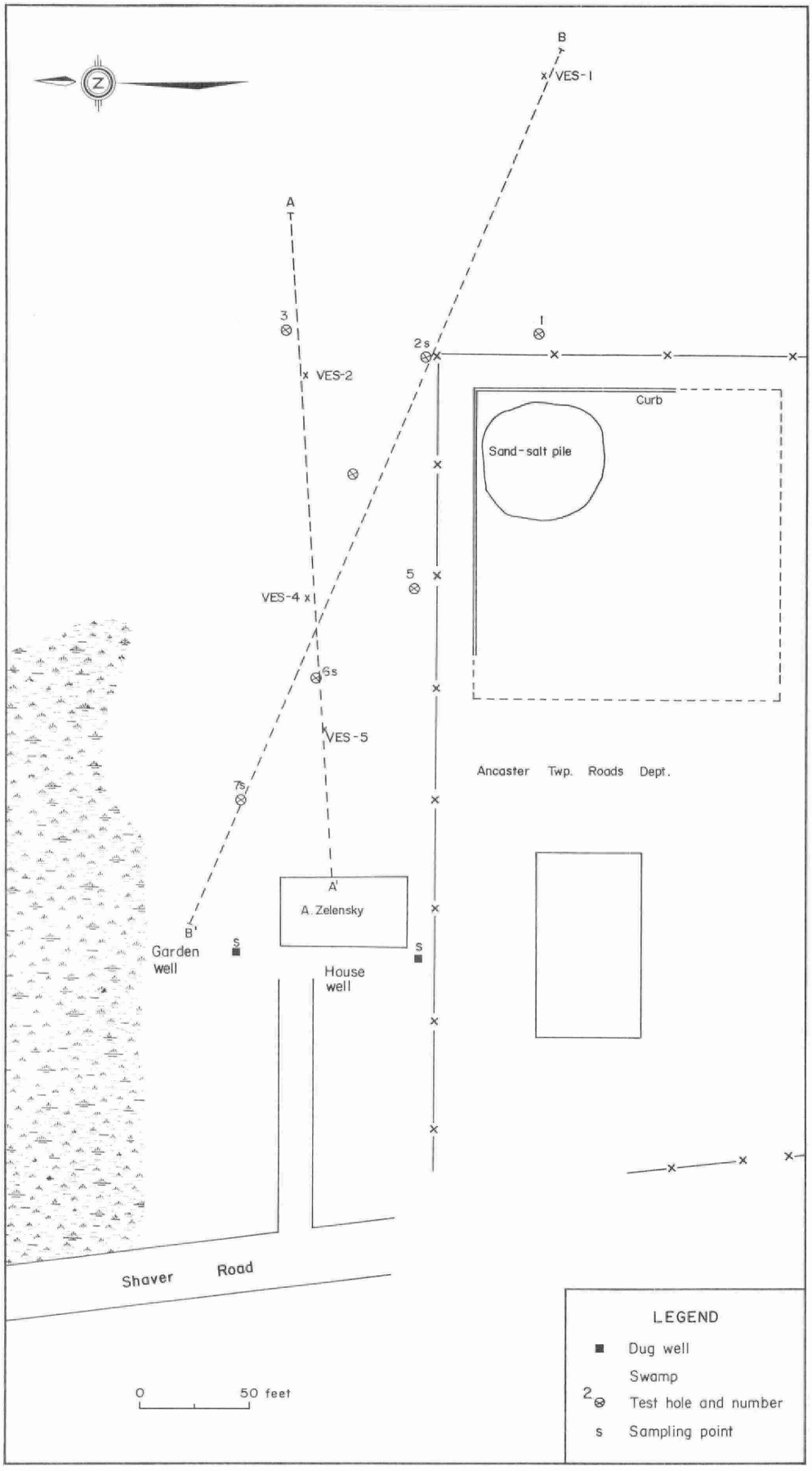

Figure 16. Location map of geophysical investigation sites.

RESISTIVITY INVESTIGATIONS OF THE SALT-WATER CONTAMINATION OF A SANDY AQUIFER IN THE TOWNSHIP OF ANCASTER

INTRODUCTION

Following a request from the former Surveys and Projects Section of the Water Quantity Management Branch, detailed resistivity investigations were carried out near the site of a sand-salt pile stored on the Township of Ancaster Roads Department property. It was reported that salt-water runoff from the sand-salt pile, being allowed to escape towards a swampy depression, was infiltrating into a shallow sandy aquifer.

As a sand saturated with salt water would exhibit a low resistivity in sharp contrast to one saturated with fresh water, it was anticipated that an electrical resistivity survey would be able to determine the areal extent and degree of salt contamination in the aquifer.

DESCRIPTION OF THE SITE OF INVESTIGATION

The surficial situation at the site is illustrated diagramatically in Figure 16. The surface of the ground generally slopes gently down in a northwesterly direction from the pile towards the swamp.

Chemical analyses of samples obtained in four test holes and two wells document the high NaCl concentrations (Table 2).

FIELD INVESTIGATIONS

An area of about two hectares was investigated by electrical methods. Electrical resistivity profiling using the collinear-dipole electrode arrangement (Bodmer and Ward, 1968) was conducted along seven parallel profiles in the east-west direction (lines 1 to 6, and 11, Figure 18) and four profiles in the north-south direction (lines 7 to 10, Figure 18). With the exception of line 11, the distance between the profiles in both directions was chosen as 25 feet. As the resistivity data was required to appear on points of a square grid with a 25-foot interval (dots in Figure 18), it was necessary to place electrodes at regular intervals of 25 feet along each profile.

The collinear-dipole electrode arrangement consists of two pairs of electrodes (dipoles) making electrical contact with the earth. One pair is used to introduce an electrical current into the ground (current dipole), the other pair (potential dipole) enables measurements of the potential difference due to the current introduction. For every position of the potential dipole, measurements are taken

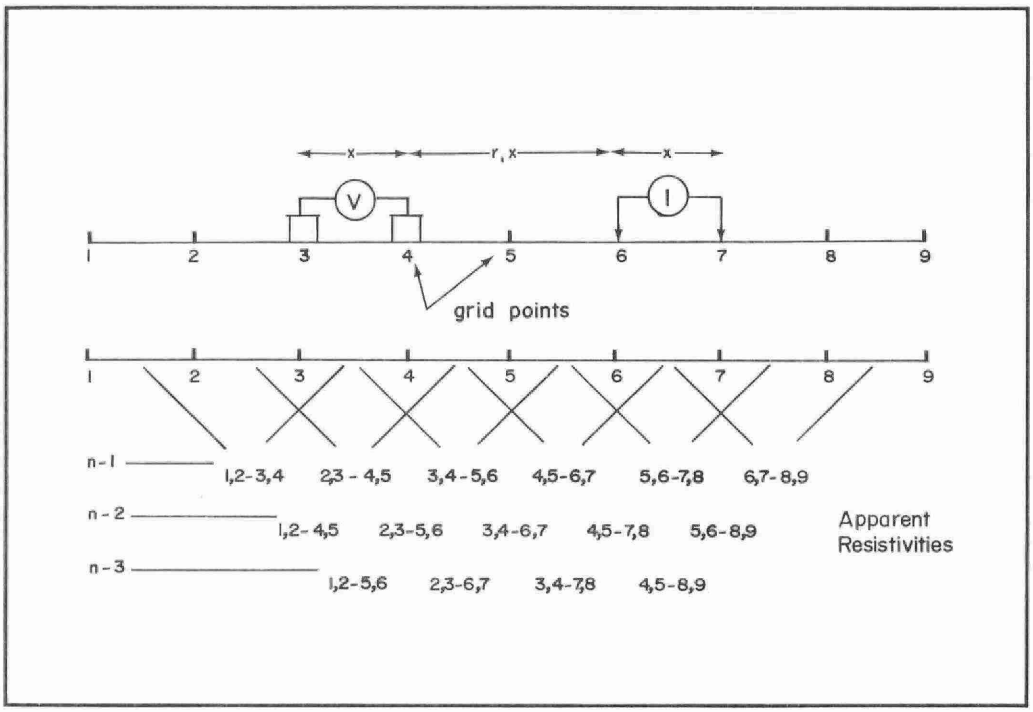

Figure 17. Collinear dipole electrode arrangement.

TABLE 2: Summary of Augering and Sampling Survey

August 7, 8, 9, 1973

Township of Ancaster

Lot 35, Concession III

Sample Point	Chloride Concentration in ppm 1973	1971
2	9,995	not sampled
4	3,290	not sampled
6	38,700*	not sampled
7	23,300	not sampled
Zalensky - Garden Well	8,640	6,790
- House Well	106	129
**Background (nearby up-gradient wells in same aquifer)		
W. C. Revie Well	19	not sampled
D. Watts Well	50	not sampled

*approximately twice the chloride concentration of sea water.
**these wells are not included in Figure 1.

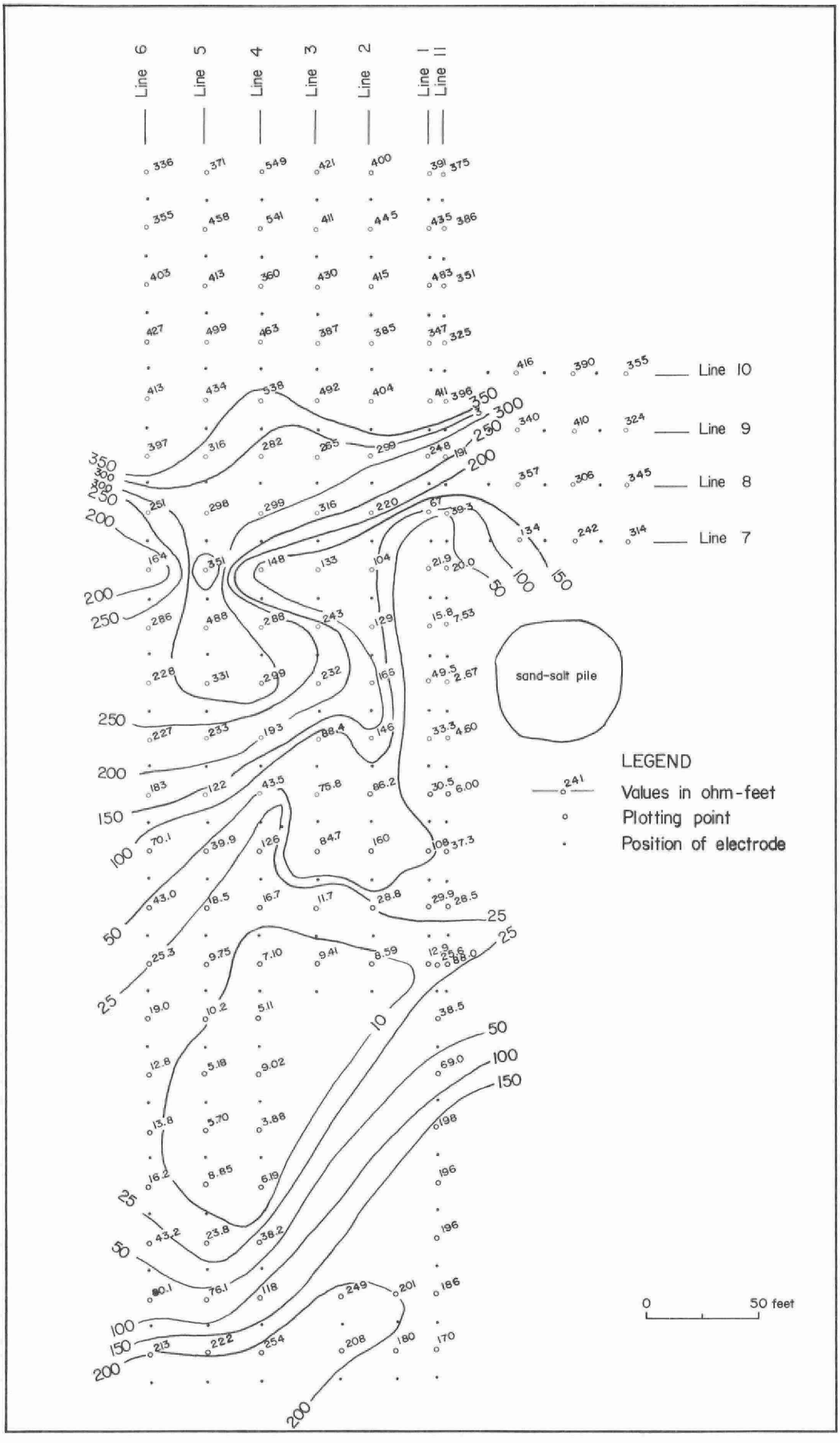

Figure 18. Resistivities at approximate depth of 15 feet.

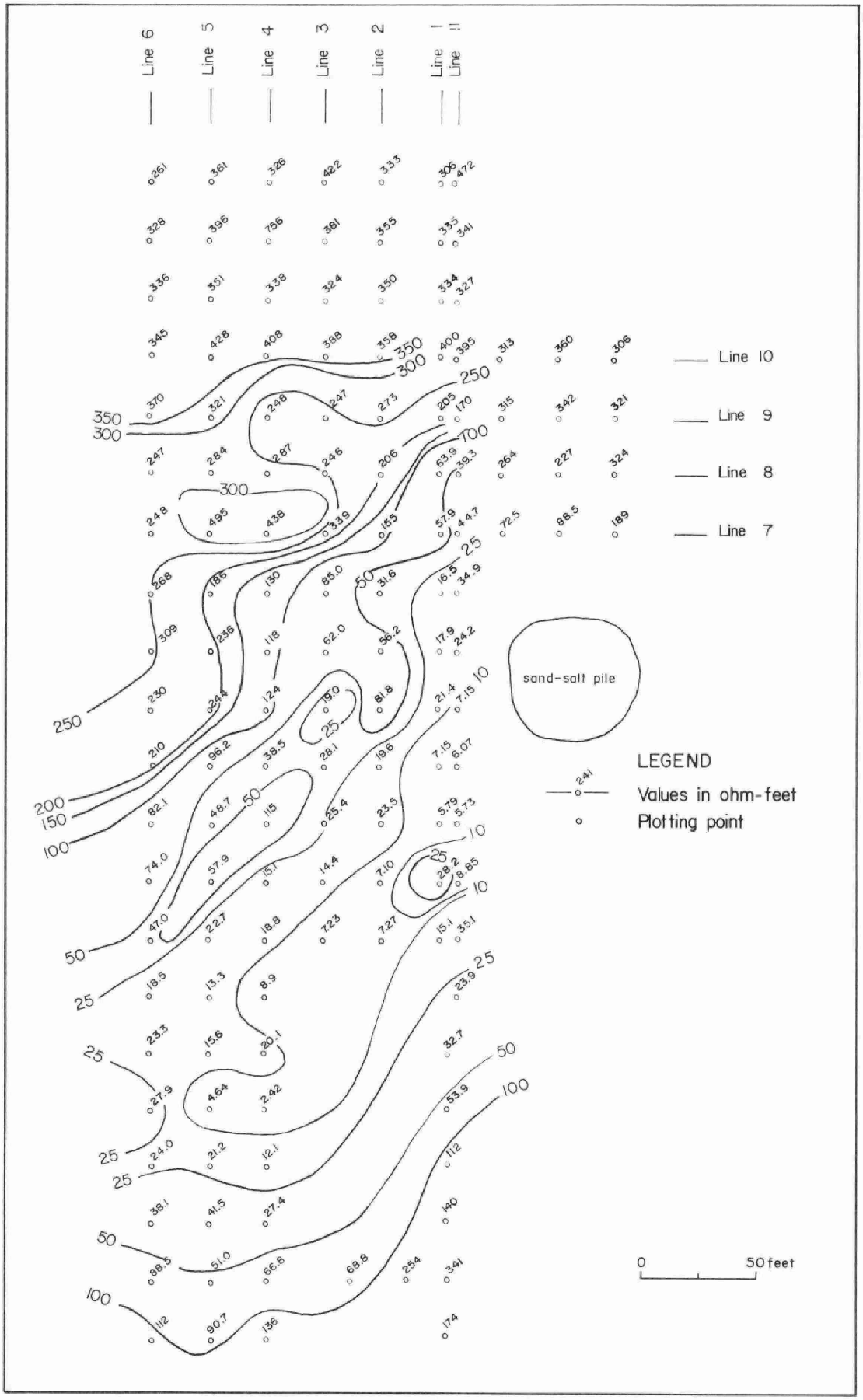

Figure 19. Resistivities at approximate depth of 20 feet.

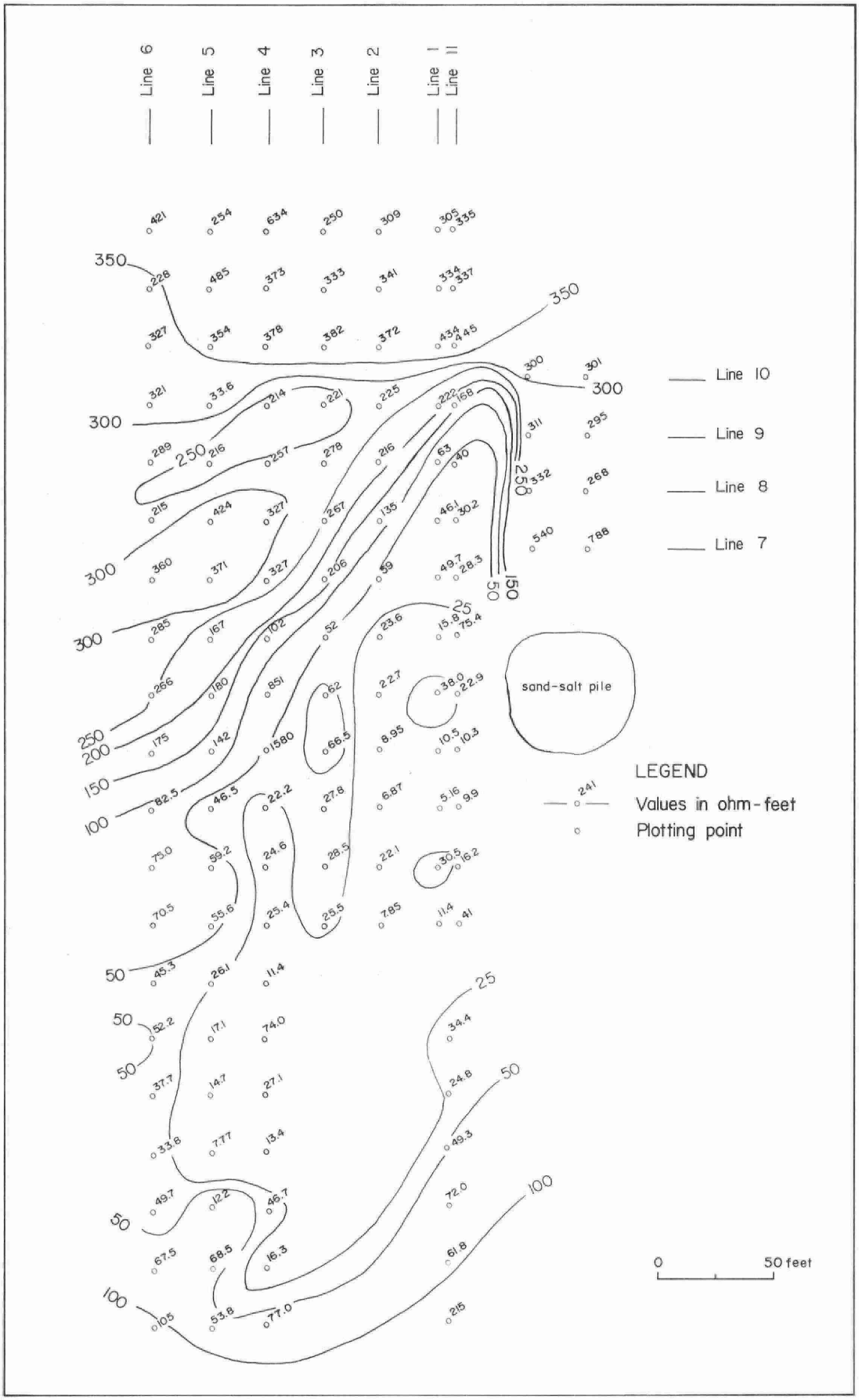

Figure 20. Resistivities at approximate depth of 25 feet.

corresponding to three distance intervals (dipole separations) of the current dipole (x.n where n = 1, 2 and 3, see diagram in Figure 17) each corresponding to a different depth of investigation. The width (x) of both dipoles is the same, i.e. 25 feet. Measurements corresponding to three different depths of investigation (15, 20 and 25 feet) are obtained at each potential dipole location (i.e. at each pair of grid points along each line).

Subsequently, five vertical electrical soundings (VES) were conducted at locations shown in Figure 16. VES-1 was conducted in the place where the sandy aquifer appeared to be saturated with fresh water, while VES-5 in a place where the NaCl concentration appeared highest. The four other vertical electrical soundings were located between these two.

RESULTS

The resistivity profiling data is plotted according to its corresponding depth of investigation (15, 20 and 25 feet) in three separate diagrams in figures 18, 19 and 20, respectively.

Two resistivity cross-sections AA' and BB' (figures 21 and 23) were constructed in order to compare the profiling data with known NaCl concentrations of samples obtained from test holes.

In figures 22 and 24, the resistivity sounding curves are shown as obtained at VES locations along AA' and BB'. From these curves, the true resistivities of individual layers can be determined and correlated with both known NaCl concentrations and with the profiling data.

ANALYSIS AND INTERPRETATION

By a close examination of each diagram and by correlation of the diagrams with each other, with known NaCl concentrations and with the vertical electrical soundings, it is possible to determine:

(1) the approximate extent of the contaminated zone of the aquifer,
(2) the direction of migration of the salt-contaminated ground water,
(3) the approximate NaCl concentrations in the ground water.

(1) All three resistivity maps (figures 18, 19 and 20) are similar as they characterize only slightly different portions of the ground. By overlaying them on top of each other, the approximate three-dimensional extent of the salt water contamination can be determined. Resistivity values above 300 ohm-feet correspond to a fresh-water-saturated sandy aquifer

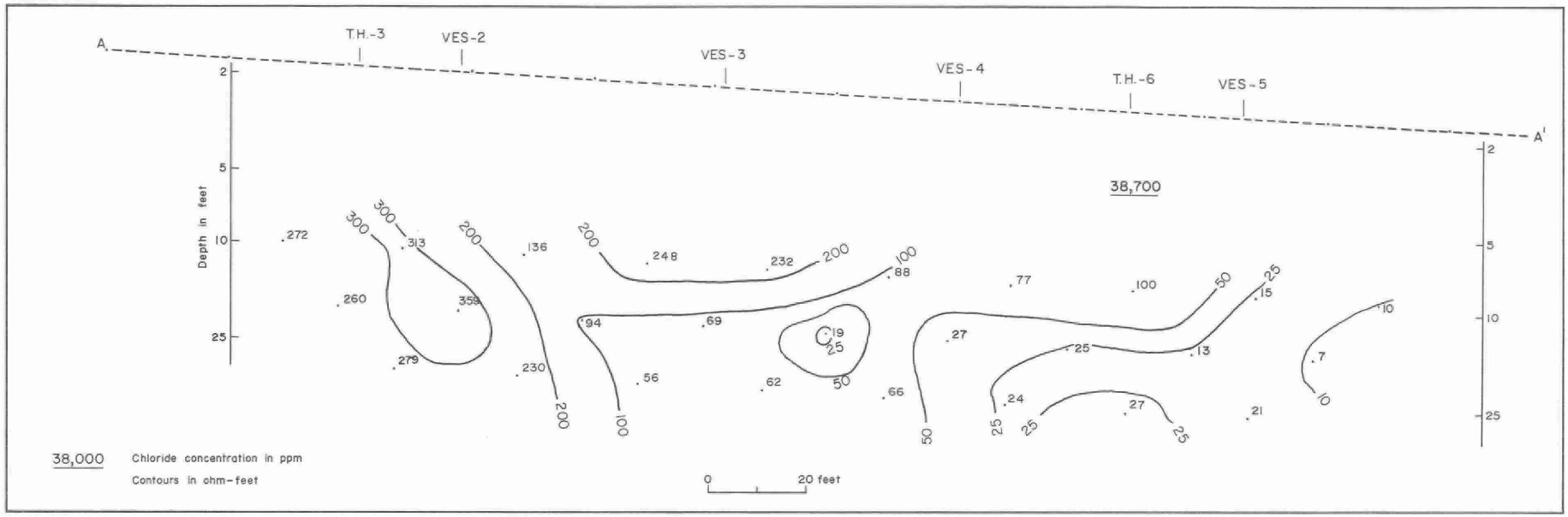

Figure 21. Resistivity section AA'.

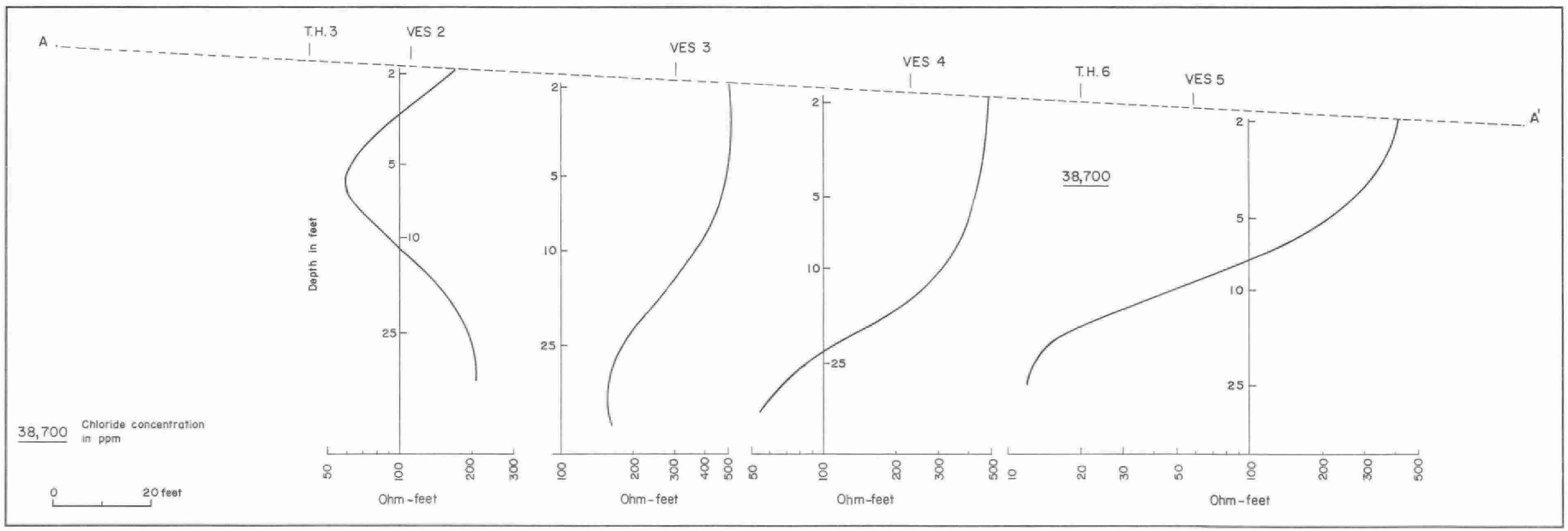

Figure 22. VES curves and test holes along section AA'.

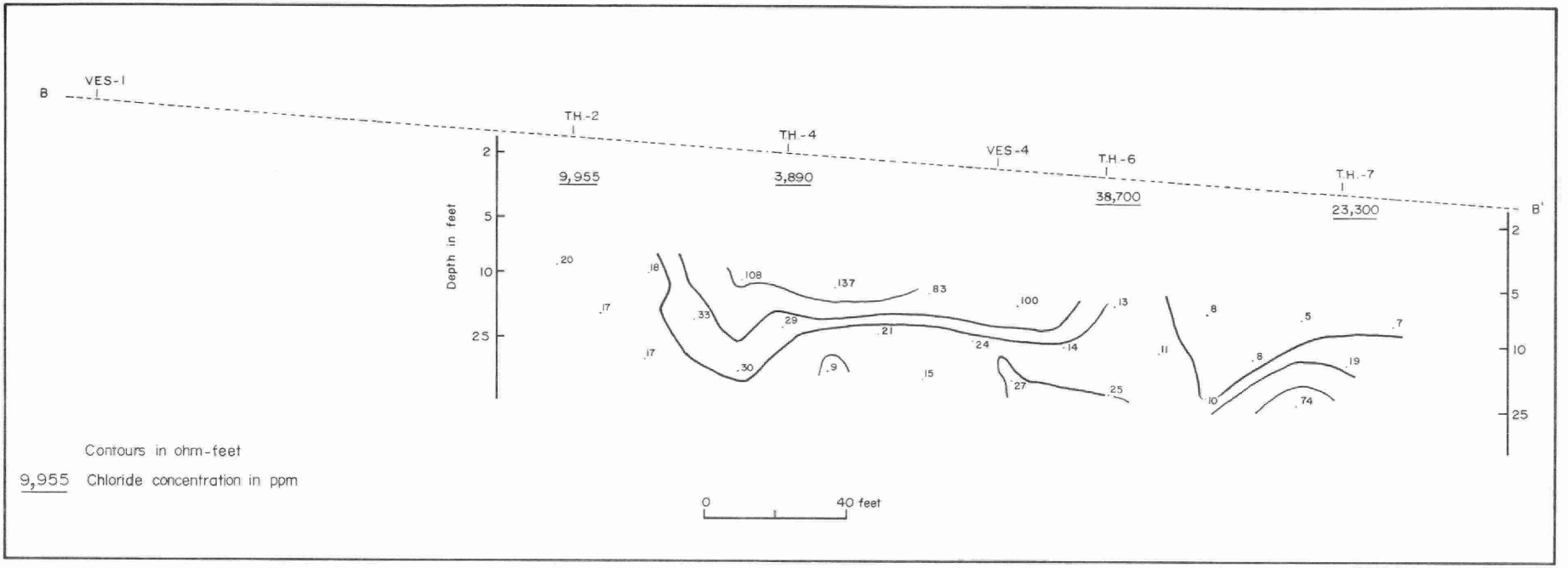

Figure 23. Resistivity section BB'.

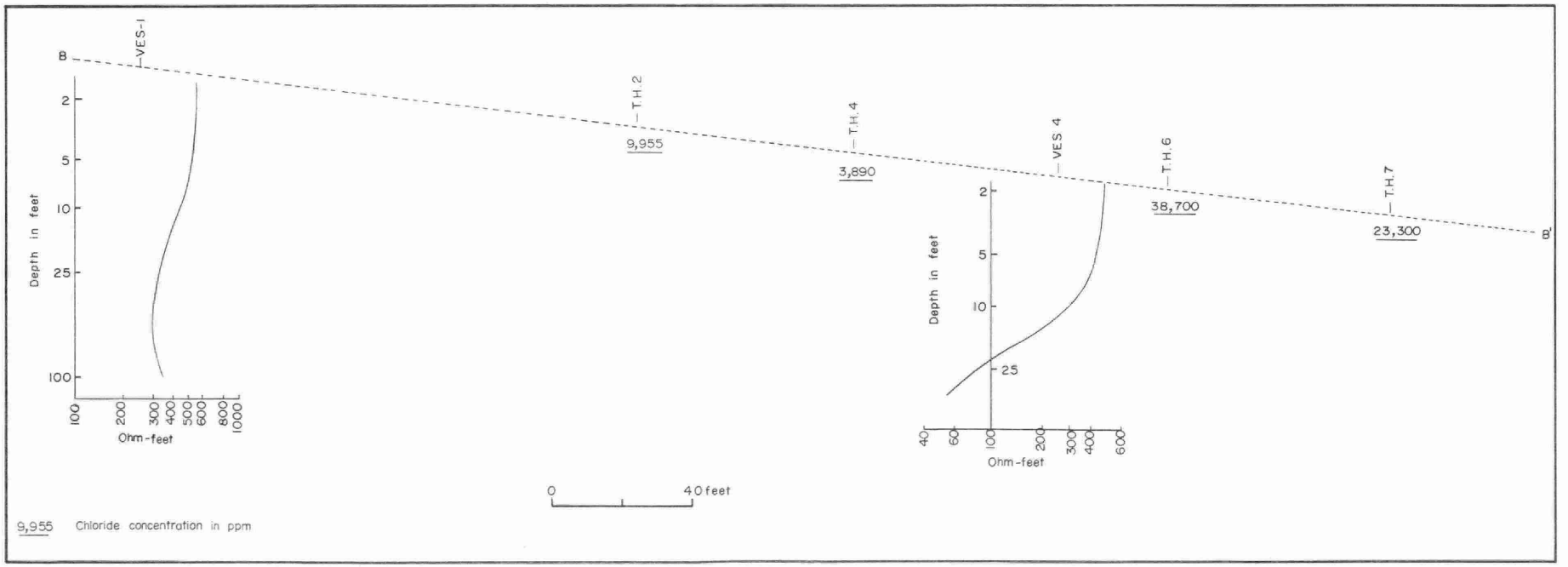

Figure 24. VES curves and test holes along section BB'.

as opposed to low resistivity values below 10 ohm-feet, which correspond to high (over 10,000 ppm) NaCl concentrations in the contaminated portion of the aquifer. The areal extent of salt-water contamination, therefore, approximates the 300 ohm-feet contour in Figure 18. The extent of the salt-contamination in the north, northwest and west directions could not be determined due to various obstacles on the surface (swamp, houses, buildings and roads). The apparent increase in areal extent of the contamination with depth (observed by overlaying all three maps) is mainly due to the nature of the collinear-dipole profiling method. As the distance between dipoles increases, the depth of investigation increases. Plotting points are kept in the centre between both dipoles; therefore, they appear on a line dipping at a 45° angle away from the potential dipole towards the current dipole, as illustrated in the sketch in Figure 17.

The VES-1 curve (Figure 24) representing resistivity conditions in the overburden containing no salt water, is in contrast with the remaining sounding curves as shown in figures 22 and 24. The resistivity cross sections in figures 21 and 23 correlated well with sounding curves in figures 22 and 24, showing the highest NaCl concentrations probably near the lower boundary of the sandy aquifer. For comparison, the known concentrations below test hole locations are given in parts per million (figures 21 and 24).

(2) The resistivity minimum is elongated in the northwest direction extending from the sand and salt pile to about 300 feet from it (figures 18, 19, and 20). It appears, therefore, that after infiltrating into the aquifer from the surface, the salt-contaminated ground water moves away from the sand and salt pile in a northwesterly direction, as the water table slopes down towards the swamp.

(3) Approximate concentrations of NaCl in the ground can be determined from the measured values of resistivity. As shown in Figure 19, the minimum observed resistivity values are lower than 3 ohm-feet. As the temperature of a salt solution is lowered, the measured resistivity values for the given solution become progressively greater. In the nomogram in Figure 25, the resistivity of solutions of NaCl is shown as a function of temperature and concentration in grains/gallon (G/G) and parts per million (ppm). If we assume the temperature of 55°F as a maximum for the ground water, then the corresponding NaCl concentration would be 7,500 ppm according to the nomogram in Figure 25. Similarly, values of 25 ohm-feet correspond to concentrations of about 1,000 ppm and values of 100 ohm-feet correspond to concentrations of about 250 ppm. These concentrations represent minimum values because ground-water temperatures are likely lower than the assumed maximum of 55°F.

Figure 25. Resistivity graph for NaCl solutions, (after Schlumberger, 1958).

The concentrations referred to above represent values for a salt-water saturated medium, in this case a sandy aquifer. The relative magnitude of concentrations in samples are consistent with the corresponding measured resistivity values (figures 21 and 23). Because this value represents NaCl concentration of a water sample, it is higher than the derived value of concentration 7,500 ppm, which corresponds to the salt-water-saturated sand. As documented by most of the VES, the unsaturated sand exhibits resistivities between 400 and 500 ohm feet.

CONCLUSIONS

Electrical methods are able to provide assistance in studying some salt-water contaminated aquifer problems. The results presented in illustrations accompanying this report document the approximate extent and intensity of NaCl contamination of a saturated sandy aquifer. They also suggest the direction of the salt-water migration. However, the success of electrical methods in such problems depends upon a high water table in sandy materials, a fairly thick saturated zone and a high enough level of dissolved salt to yield an unambiguously low earth resistivity compared to that in the uncontaminated areas.

PART IV

AN APPLICATION OF THE MAGNETIC METHOD TO FINDING BURIED FUEL STORAGE FACILITIES AS POTENTIAL SOURCES OF GROUND WATER CONTAMINATION

AN APPLICATION OF THE MAGNETIC METHOD TO FINDING BURIED FUEL STORAGE FACILITIES AS POTENTIAL SOURCES OF GROUND WATER CONTAMINATION

INTRODUCTION

In September 1972, a request was received from the former Surveys and Projects Section of the Water Quantity Management Branch to find abandoned underground fuel storage facilities in the Town of Sioux Lookout (District of Kenora) and at Shabaqua Corners (District of Thunder Bay). From discussions with the Surveys and Projects Section representative, it was determined that the underground storage facilities were 2,000-gallon, steel fuel tanks buried at shallow depths. It was anticipated that both magnetic and electromagnetic methods would likely be of considerable assistance in locating the tanks. Through the courtesy of the geophysical group of the Division of Mines, Ministry of Natural Resources, a fluxgate magnetometer was made available for measurements of the vertical component (ΔZ) of the total magnetic field.

In order to evaluate the application of the magnetic method to the above-mentioned problem, an experimental magnetic survey was conducted in a selected test area in the Village of Madoc (County of Hastings) in October 1972. Following the successful results obtained during the experimental survey, magnetic surveys were conducted in the Town of Sioux Lookout and at Shabaqua Corners in November 1972.

THEORETICAL ASSUMPTIONS AND CONSIDERATIONS

Prior to the experimental magnetic survey, the following assumptions were made:

(1) the geological situation was considered to be homogeneous within the area of investigation,
(2) no iron ore deposits were considered to be at the site,
(3) the fuel tank was considered to be magnetized chiefly by the earth's magnetic field.

Diurnal variations of the earth's magnetic field were expected to be small. It was anticipated that any artificial disturbance of the magnetic field, such as that caused by moving and parked cars, power lines, scrap metal, etc., would be considerably higher.

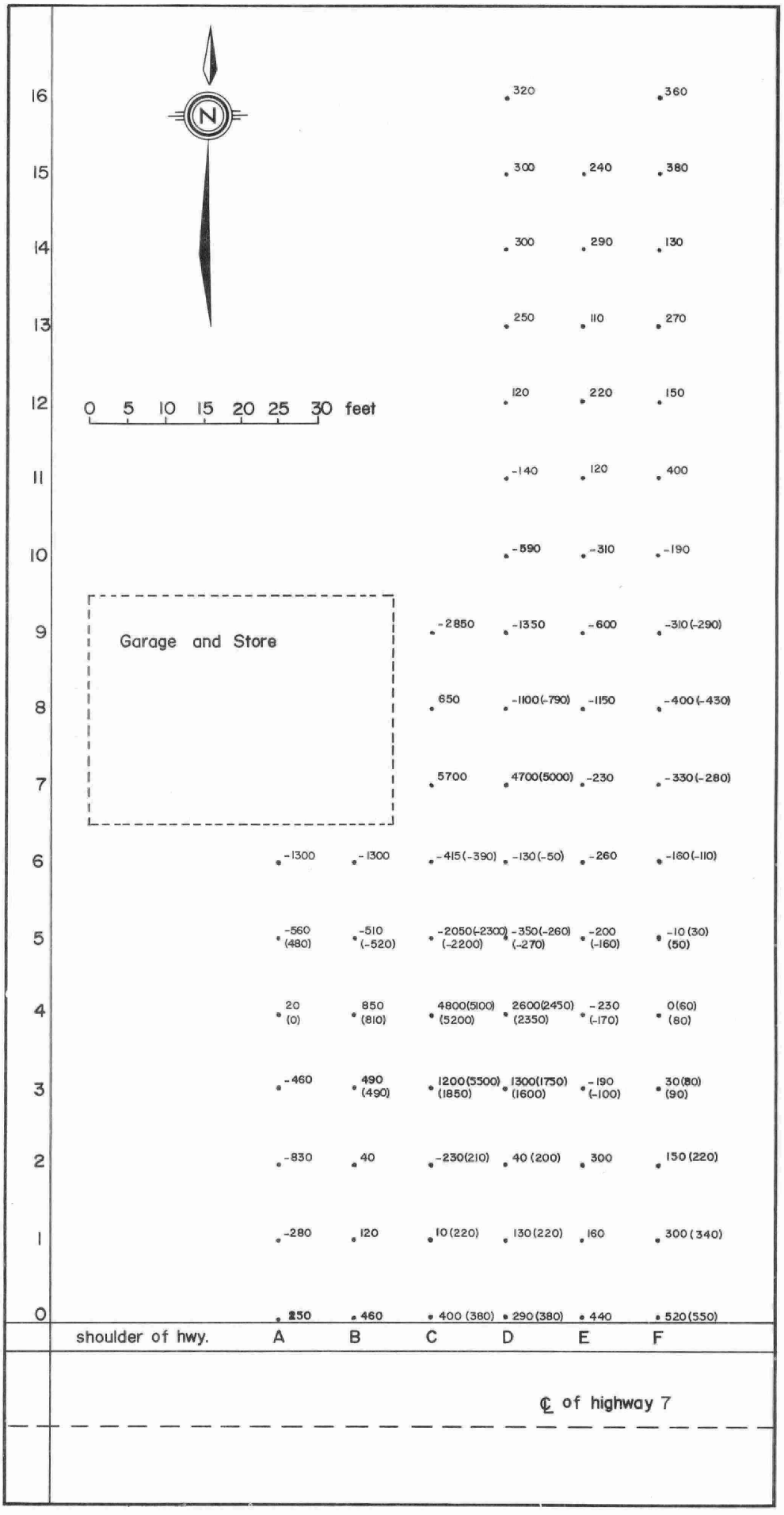

Figure 26. Location of magnetic survey stations - Madoc.

It was further expected that a magnetic anomaly due to a buried fuel tank would be:

(1) intense, having a magnitude several times that of both the natural field and any artificial disturbances resulting from cars, scrap metal, etc., because of the large mass of the tank and its shallow depth of burial,
(2) of small lateral extent due to the limited size of the tank and its shallow depth of burial.

In the northern hemisphere, a ΔZ anomaly due to a buried magnetic body would reach minimum values on its north side. The maximum positive ΔZ anomaly would occur south of a point vertically above the centre of the body; however, both the shape and magnitude of the ΔZ anomaly as a result of a buried fuel tank could be expected to be seriously distorted by the noise resulting from artificial magnetic sources located on the surface. Because of this distortion, any ΔZ anomalies could likely be interpreted only qualitatively. The reliability of the method then would depend on the ratio of the amount of noise present (caused by natural field variations and artificial disturbances) and the strength of the signal. If the mass of the metal object were large and its depth of burial small, the magnetic anomaly (signal) due to the object would have a large magnitude and therefore, would be detectable, provided that the magnitude of artificial disturbances would not exceed half that of the signal.

EXPERIMENTAL SURVEY - VILLAGE OF MADOC

The experimental magnetic survey conducted in the Village of Madoc was designed to determine the validity of all the assumptions and considerations stated above. The test area that was selected is in a Precambrian environment similar to that in the Town of Sioux Lookout and at Shabaqua Corners and consists of known, underground, fuel storage facilities. Buildings, cars (both parked on the site and moving along the road) and miscellaneous metal objects situated on the surface were present at the site and were expected to contribute to a high noise level (see Figure 26).

Methodology

A crew consisting of two men (the operator of the fluxgate magnetometer and the recorder of the data) was used. In order to investigate the site, measurements of the vertical component (ΔZ) of the earth's magnetic field were taken at points on a square grid. The grid interval was selected according to the approximate horizontal dimensions of expected anomalies. In order not to overlook important anomalies, the grid interval was chosen according to the

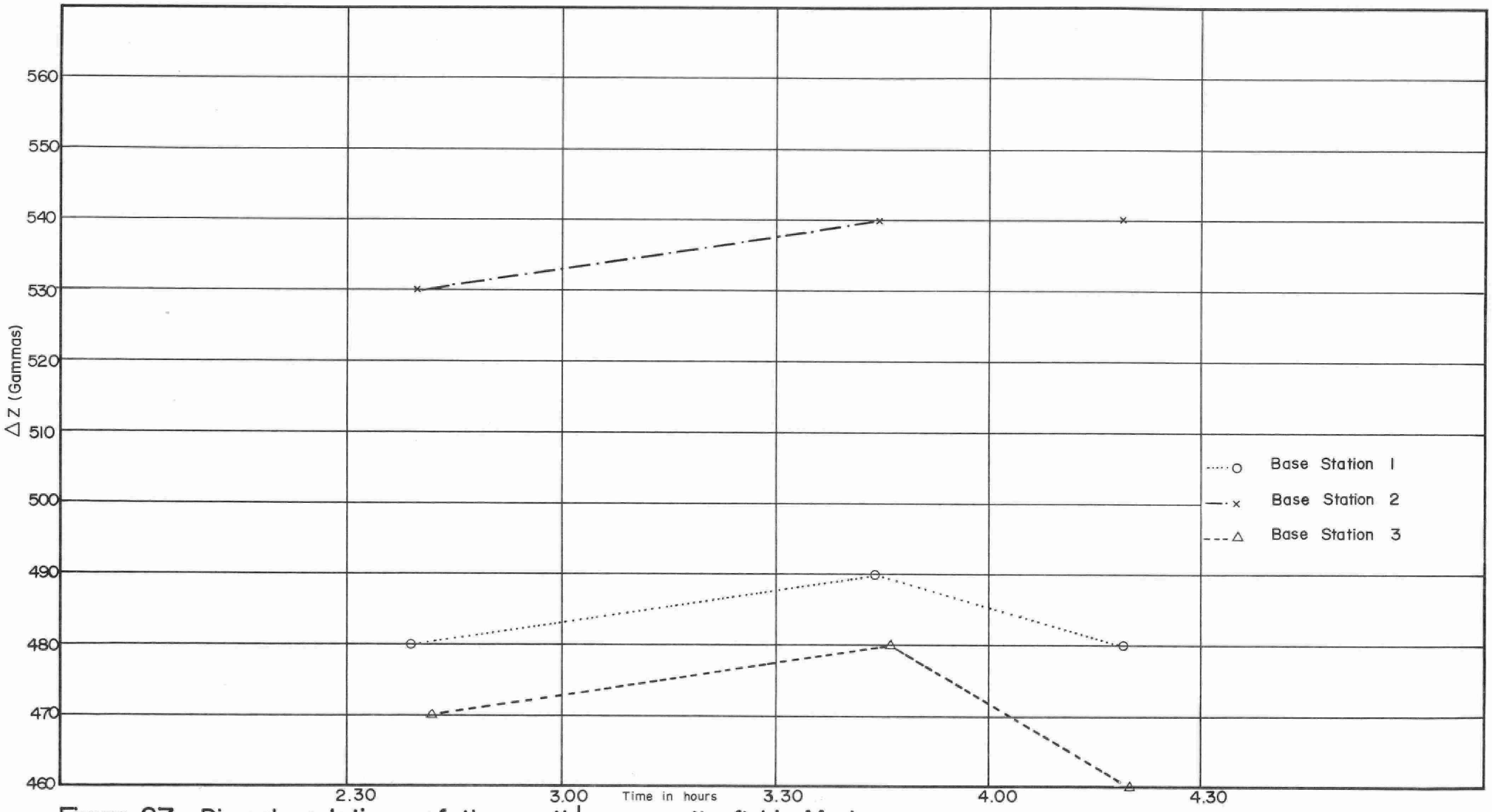

Figure 27. Diurnal variations of the earth's magnetic field - Madoc .

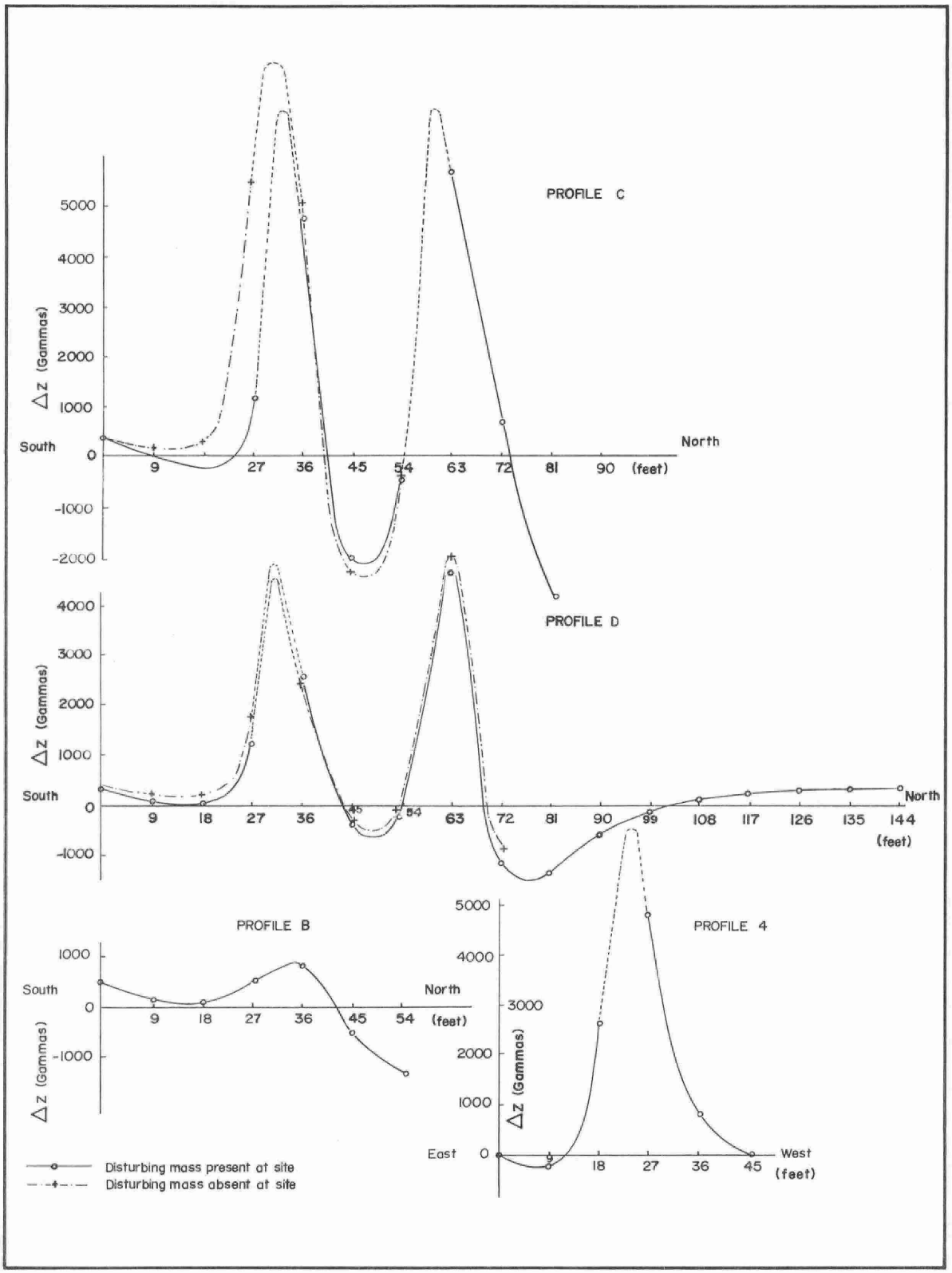

Figure 28. Vertical component (Δ Z) of magnetic field along sections - Madoc.

Sampling Theorem, viz., it was small enough to provide an effective coverage of the site investigated. The grid interval chosen was approximately nine feet (see Figure 26).

In addition, three reference stations were selected in an area where artificial disturbances were absent, far enough from the site and from any metal objects, buildings, etc., on the surface. At these stations, the measurement of ΔZ were recorded at certain intervals and then plotted graphically as a function of time (Figure 27) in order to determine diurnal variations of the earth's magnetic field. Readings taken at all grid points were then corrected for these variations. The variations were found to be negligible in comparison with the artificial disturbances for which readings could not be corrected.

The known fuel storage facilities were detected without difficulty. Magnitudes of positive ΔZ anomalies corresponding to buried fuel tanks were found to be about 5,000 gammas, i.e., nearly ten times more intense then those caused by the natural magnetic field which varied from 400 to 500 gammas (Figure 28).

As was also expected, the anomalies were of a relatively small lateral extent, thus indicating that the fuel tanks were buried at shallow depths. The level of noise resulting from artificial magnetic sources situated on the surface was relatively high, reaching twice the magnitude of the natural magnetic field. However, this noise level of twice the natural field was small compared with the anomaly level of ten times the natural field. Therefore, the noise did not appreciably mask the positive ΔZ anomalies or distort seriously the magnitudes of the anomalies. Approximately one hour was needed to take measurements on 130 points.

Conclusion

It was concluded from the experimental survey that a magnetic method could be successfully applied to a problem of finding abandoned buried fuel storage facilities in areas with environments similar to that in the Village of Madoc. It also appeared that the aforementioned assumptions and considerations regarding the magnetic method were correct.

TOWN OF SIOUX LOOKOUT AND SHABAQUA CORNERS

On November 8 and 9, a magnetic survey was conducted in the Town of Sioux Lookout and at Shabaqua Corners. The problem was to determine whether or not unknown underground fuel storage facilities were present in the vicinity of a former

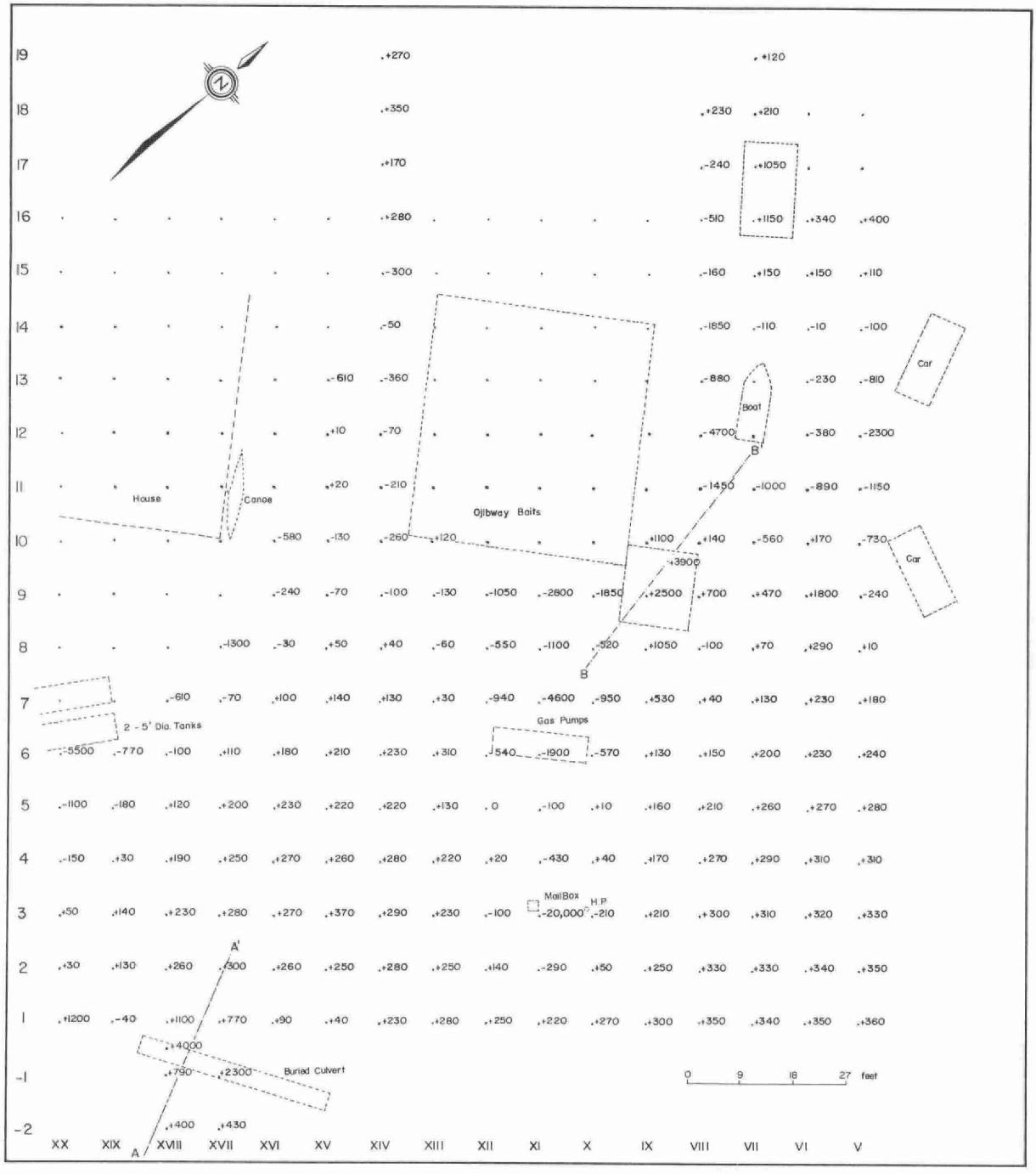

Figure 29. Location of magnetic survey stations - Sioux Lookout.

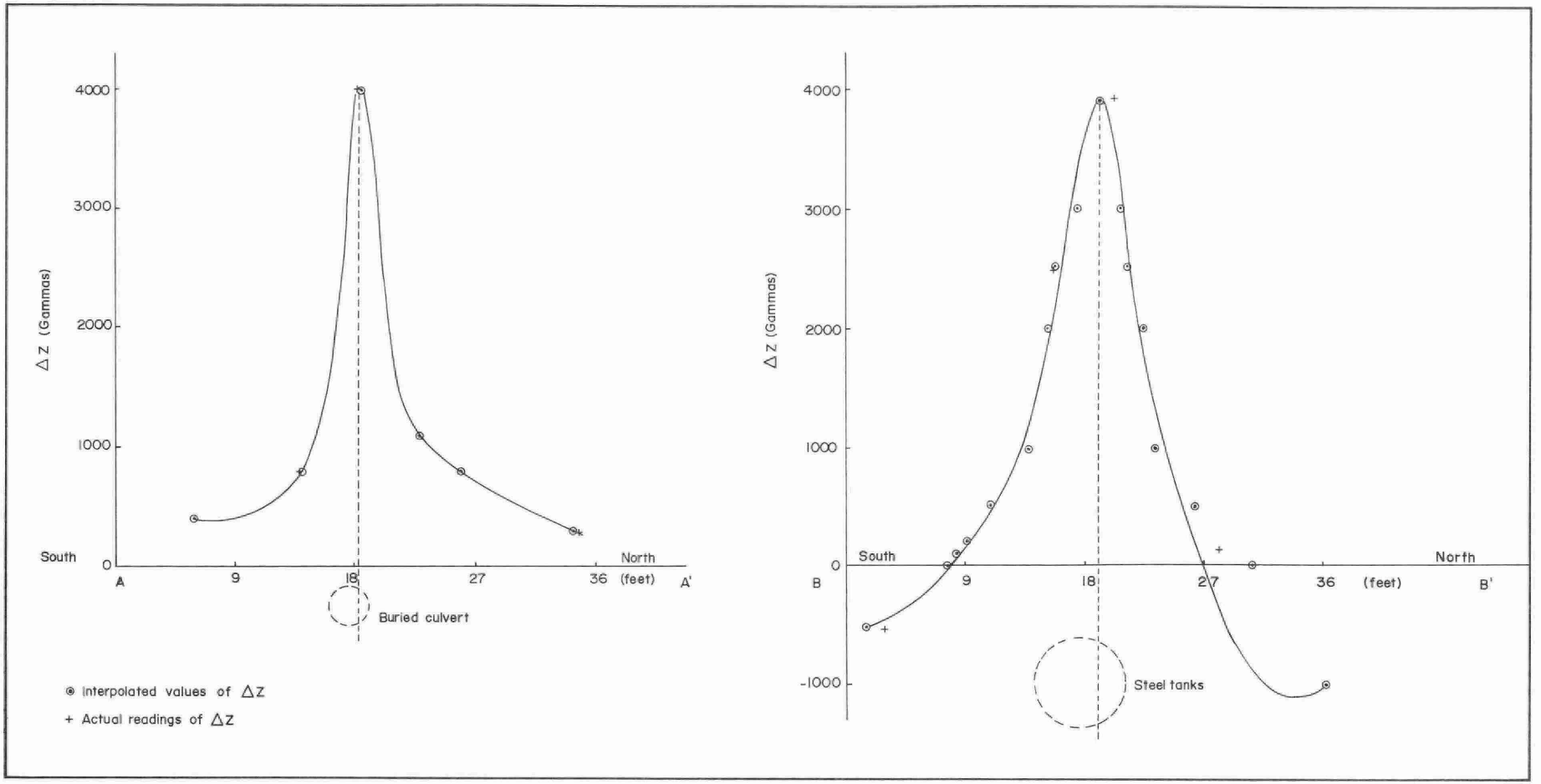

Figure 30. Vertical component (ΔZ) of magnetic field above buried object — Sioux Lookout.

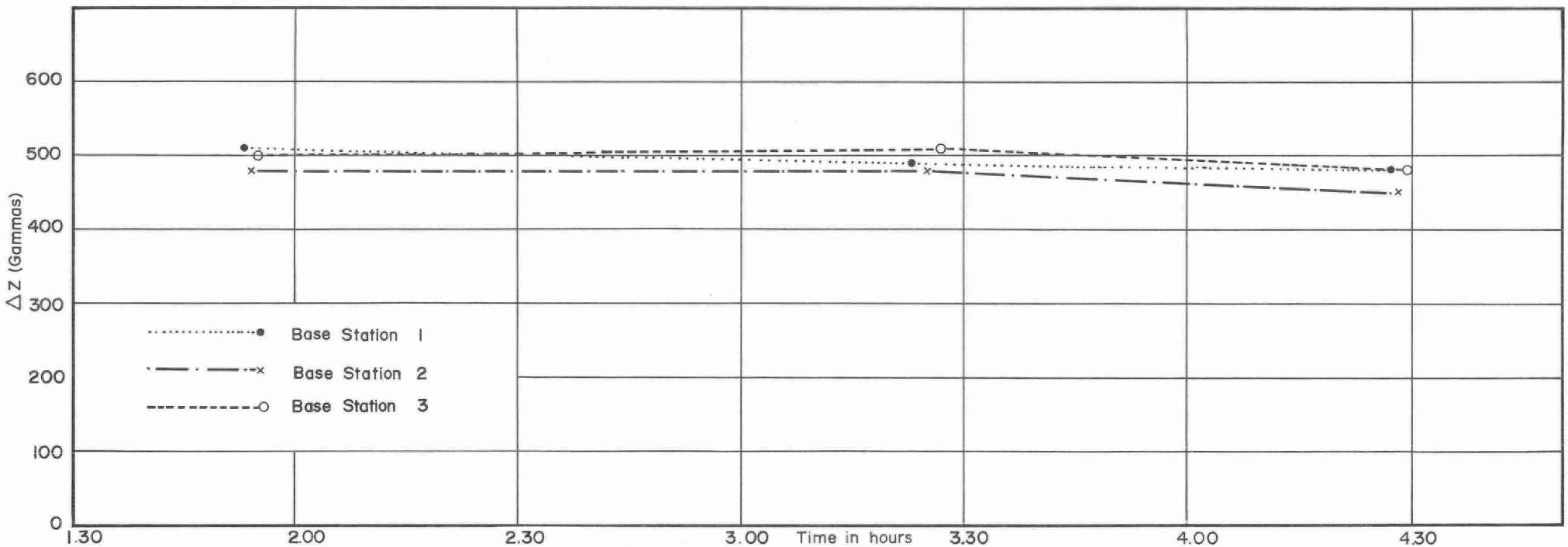

Figure 31. Diurnal variations of the earth's magnetic field - Sioux Lookout.

gasoline station at Sioux Lookout and at an existing gasoline station on Highway 17 at Shabaqua Corners.

Town of Sioux Lookout

On the Sioux Lookout site, magnetic measurements were taken on points of a square grid. The grid interval was chosen to be approximately nine feet, the same as in the experimental survey in Madoc. The locations of grid points together with the surficial situation are presented in Figure 29. As can be observed, some magnetic or partly magnetic objects were situated on the site, thus distorting magnetic measurements.

Interpretation

The regional magnetic field at the site appeared to be around 300 gammas. Diurnal variations of the magnetic field were not appreciable at the time of the survey, as demonstrated in Figure 31. Three strong positive ΔZ anomalies, two of which are shown in Figure 30, were found at the site. The one located in the southwest corner of the map (Figure 29, line AA') corresponds to a shallow, partially buried magnetic body elongated in an east-west direction, visually identified as a metal culvert. The cross-section of the anomaly in the north-south direction is presented at the bottom of Figure 30. A second anomaly, located approximately at the central part of the map (Figure 29, line BB') near the southwest corner of a building (store), corresponds to two known fuel storage tanks buried side by side. As the relative magnitudes of both the above-mentioned anomalies are in the same range (approximately 4,000 gammas), this suggests that the fuel storage tanks having appreciably greater masses are, therefore, buried at a greater depth than the culvert.

The third positive magnetic anomaly, approximately four times less intense than the other two, can be observed in the northeast corner of the map (Figure 29). Because of its relatively small magnitude (1050 to 1150 gammas) and its location, this anomaly did not appear to indicate a buried fuel storage tank and was not, therefore, further investigated.

Conclusion

Aside from known fuel storage tanks, no other buried fuel storage facilities appeared to be present under that part of the site investigated.

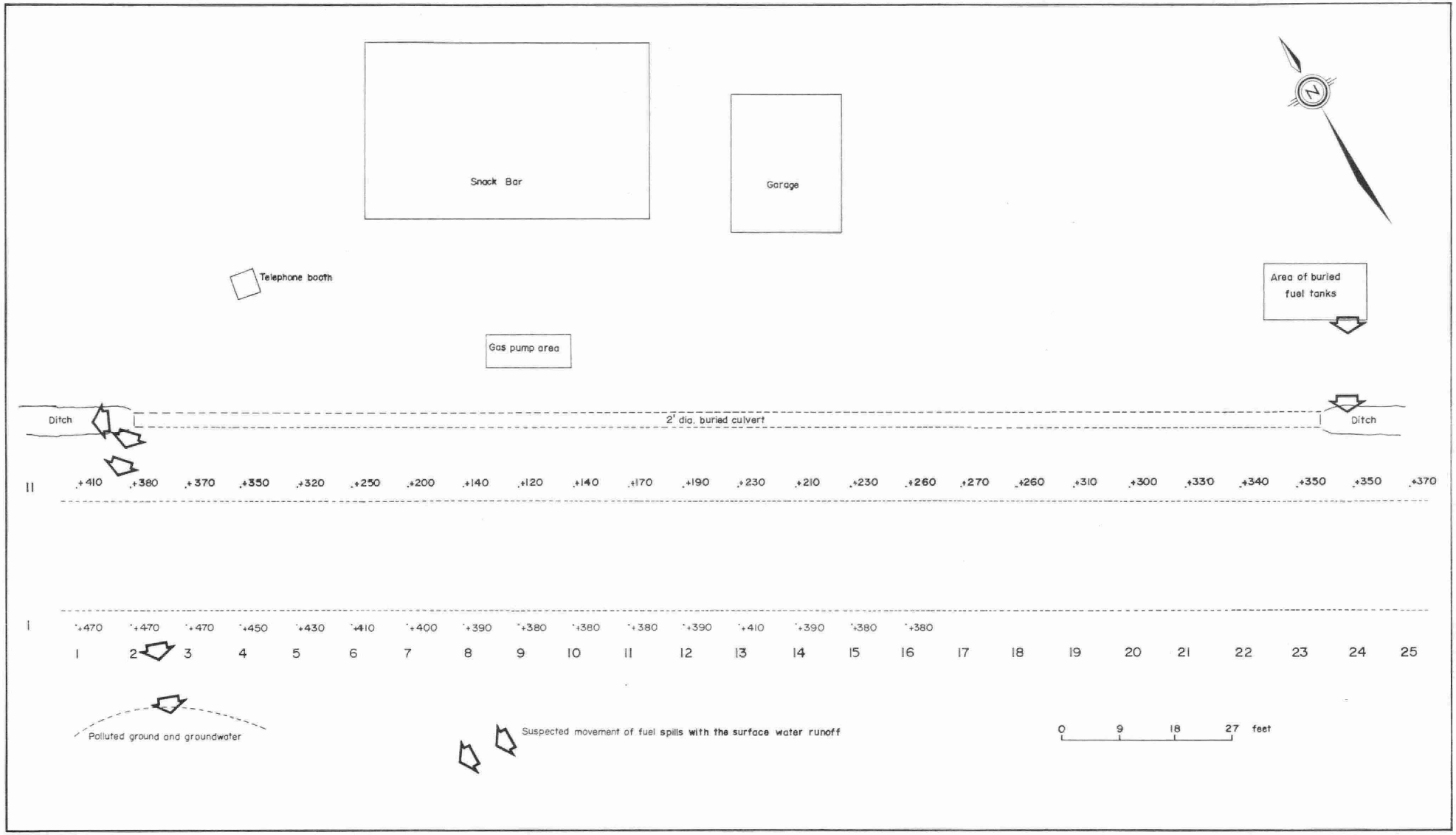

Figure 32. Location of magnetic survey station - Shabaqua Corners.

Shabaqua Corners

The initial requirement to find unknown buried fuel facilities at this site was modified by Mr. Roy McArthur, the Surveys and Projects representative. Following a discussion with the owner of the property, it was decided that a complete areal investigation of the site would not be attempted. Instead, geological and hydrogeological conditions at the site were considered and analysed from the ground-water pollution point of view. The situation at the site is shown in Figure 32. During the investigation, the problem of whether or not any old pipes or culverts were buried under the highway surface needed to be solved. For this purpose magnetic measurements were taken along two, parallel, approximately east-west traverses (profiles I and II in Figure 32), one situated on each side of Highway 17. The vertical component ΔZ of the earth's magnetic field was measured at equidistant points along each traverse. The interval between any two successive points was approximately nine feet. No metal objects were found extending under the highway surface. Also, a reconnaissance magnetic survey was conducted to test for unknown fuel storage facilities just north of Highway 17 in the vicinity of the known buried fuel tanks and in the area between these tanks and the existing fuel pumps. Besides the known tanks, no other fuel storage facilities appeared to be present in this area.

During the carrying out of the reconnaissance magnetic survey, a possible source of contamination of the ground and of the ground water was discovered. Fuel spilled during filling of the known fuel storage tanks appeared to be moving, by itself or mixed with surface rain water, towards a ditch on the north side of Highway 17, moving along the ditch and reaching an opening in a buried culvert and possibly moving through or along the culvert. The culvert situated on the north side of the highway was traced along its entire length using measurements of ΔZ. At a distance of nearly 200 feet along the culvert, the other opening of the culvert was found and polluted ground encountered. Here the spills, mixed with rain water, appeared to move along the ditch and entering the permeable materials at the bottom of the ditch and under the highway. Contamination as a result of the fuel spills appeared to be transmitted beneath the highway where it appeared on the south side of the highway seriously polluting both ground materials and ground water.

Conclusion

Besides known buried fuel tanks, no other fuel storage facilities appeared to be situated under those portions of

the site which were investigated by the magnetometer survey. Underground metal pipes or culverts were discovered and/or traced without difficulty, thus assisting in solving the contamination problems at the site.

SUMMARY AND CONCLUSIONS

The assumptions and expectations originally stated for magnetic surveys proved to be correct. The magnetic method appears to be a suitably effective and economical method for finding buried fuel storage facilities as was demonstrated during investigations of all the three locations. The method was also found to be useful as an effective technique for assisting investigators in finding and delineating other shallowly buried metal objects such as pipes, culverts, etc.

PART V

AN APPLICATION OF GEOPHYSICAL WELL LOGGING TECHNIQUES TO A GROUND WATER PROBLEM AT L'ORIGNAL

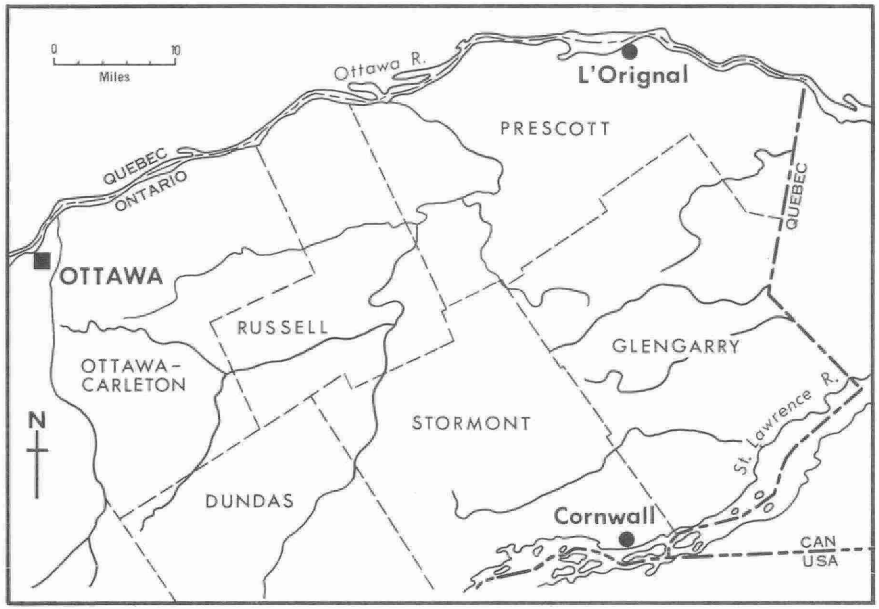

Figure 33. General map of eastern Ontario.

AN APPLICATION OF GEOPHYSICAL WELL LOGGING TECHNIQUES TO A GROUND WATER PROBLEM AT L'ORIGNAL

INTRODUCTION

In the winter and spring of 1972, a test-drilling program was carried out at the Village of L'Orignal, County of Prescott, Ontario (see Figure 33) as a continuation of a ground-water availability study to provide for the establishing of a ground-water supply for the Village. This program was undertaken by what was formerly the Water Quantity Management Branch of the Ministry of the Environment to determine potential well yields and local aquifer characteristics.

Four eight-inch diameter test wells (TW1-72, TW2-72, TW3-72, TW4-72) were installed with a cable-tool drilling machine at the locations shown on Figure 34. The wells were drilled through the overburden into the bedrock of the Rockcliffe Formation. Aquifer and well-performance tests were executed. A water-quality problem was encountered in test well TW3-72.

Test well 3-72 (TW3-72) is located at the L'Orignal playground in the northern part of the Village (Figure 34). The test well was completed to a depth of 160 feet. The well was cased to a depth of 47.5 feet and the static level on completion was 22.7 feet. Its driller's log is shown on the left side of Figure 36.

Chemical analysis of a pumped sample yielded a chloride concentration of 210 ppm, while a depth sample from 160 feet showed a chloride concentration of 974 ppm. Both levels are too high to be desirable for human consumption.

In an attempt to improve the quality of the water produced, it was planned to grout the well back to approximately 154 feet; however, plugging was inadvertently completed to a depth of approximately 135 feet. The water quality did not improve to desirable levels, as the chloride concentration remained near 150 ppm.

Geophysical techniques were then applied to determine water-bearing zones and their hydrological characteristics, and to further define the lithology of the bedrock aquifer, in order that zones responsible for the influx of high chloride water may be identified and then plugged off. It should be noted that the complete driller's log and information on water-bearing zones were not available at the time of geophysical field work and initial interpretation.

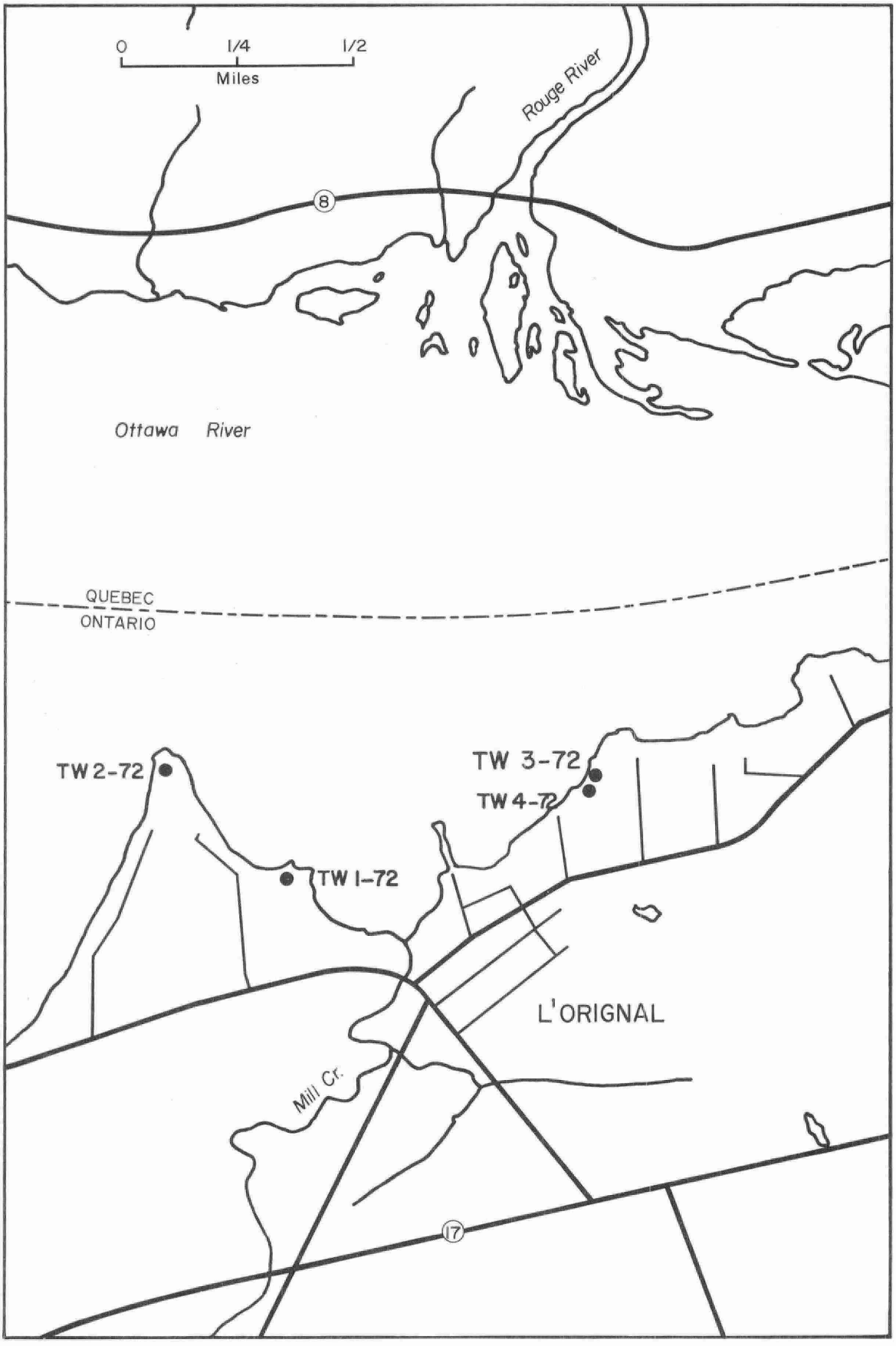

Figure 34. Test drilling sites at L'Orignal.

GEOPHYSICAL WELL LOGGING IN TW 3-72

The following probes were used in logging TW3-72:

Caliper,
Natural Gamma Ray,
Spontaneous Potential,
Single-Point Resistance,
Temperature,
Flowmeter.

In order to collect information necessary for the construction of a lithological log of TW3-72, the group of logs obtained from the caliper, natural gamma ray, spontaneous potential and single-point resistance probes were used. Although the four types of logs and their basic interpretations are discussed separately in the paper, they were interpreted conjunctively by correlation with each other. The temperature and flowmeter logs were used during pumping tests to detect zones of water movement and inflow.

Caliper Log

The caliper probe, when lowered in the well, continuously records the changes in the diameter of the well with depth. The probe has three motor-driven arms that can be opened or closed from the surface. The caliper log presented in Figure 35 indicates the presence of several zones of increased diameter in the well. An increase of approximately one inch in the diameter of the eight-inch hole was recorded at depths from:

47 to 52
82.5 to 95
97.5 to 105
111 to 116
117 to 125
and 126.5 to 132 feet

Slightly smaller increases in the diameter of the well were recorded at depths from 72 to 82 and from 106 to 108.5 feet.

Geological Interpretation

As the well was known to penetrate alternating layers of green shale and light-grey, fine-grained sandstone of the Rockcliffe Formation, the increased diameters noted in the caliper log were interpreted to correspond to the shale beds, as the shale was assumed to be softer and less competent than the sandstone. The sandstone was assumed to be hard and therefore, not expected to exhibit enlarged hole diameters.

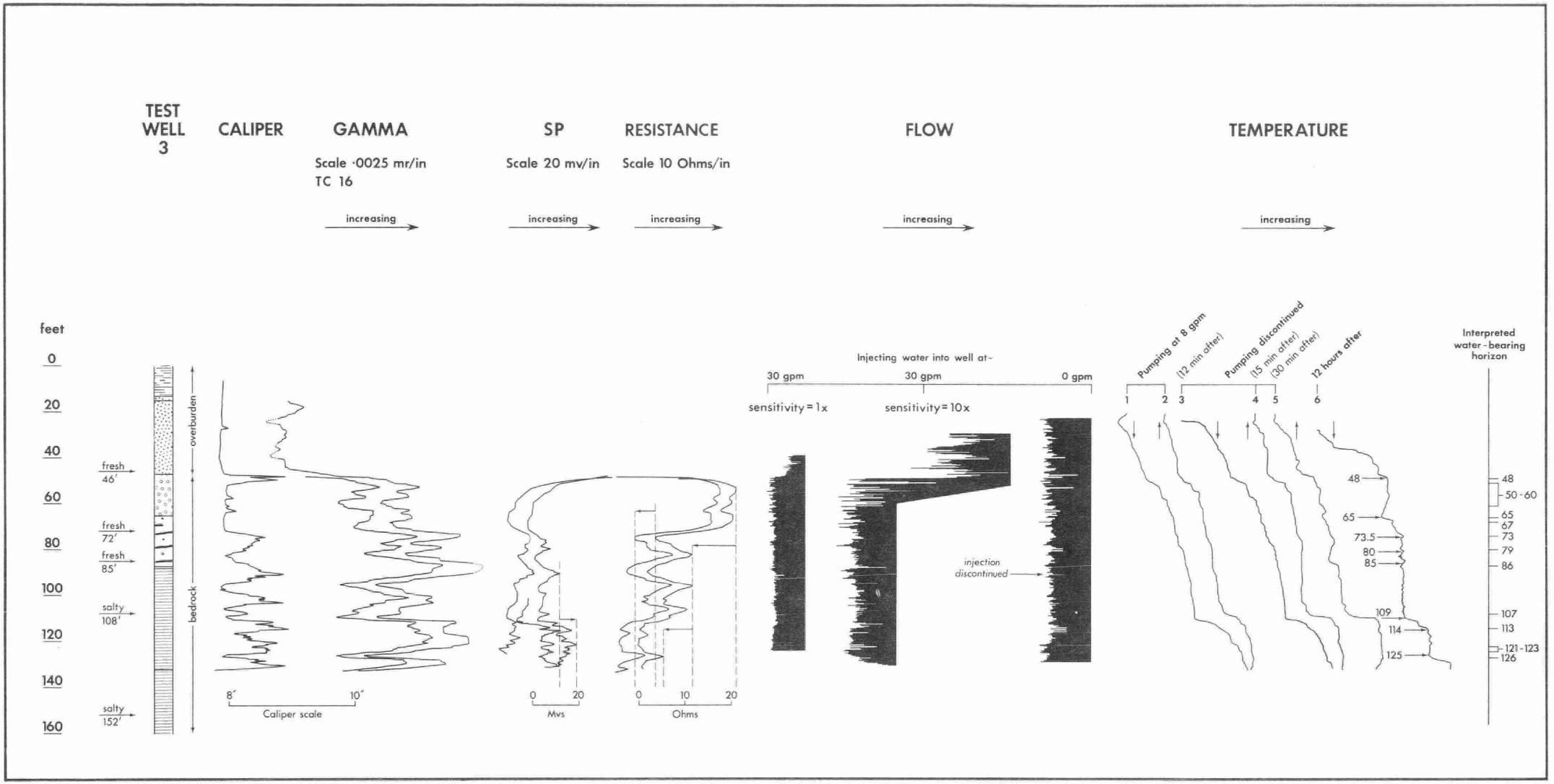

Figure 35. Composite log of test well 3 in L'Orignal.

However, if the sandstone were weathered or cracked, or formed thin seams which could have cracked or broken with the impact of the drill, an enlarged well-diameter could be encountered. By correlating the caliper information with that obtained from other geophysical logs, this ambiguity was resolved.

Natural Gamma Ray Log

A natural gamma ray log is a continuous record of the natural radioactivity of formations penetrated by the borehole. The natural gamma radioactivity is proportional to the content of radioisotopes (Uranium 238, Thorium 232, Potassium 40) disseminated in the rock surrounding the borehole. It is also a function of the density of the rock around the borehole. An increase in the rock density results in a decrease of the recorded natural gamma radioactivity.

For a given rock, the hole diameter also affects the measured radiation. If the diameter of the well is not constant, this may influence the measured gamma ray activity to the extent that it requires correction.

In common sedimentary rocks, Potassium 40 is usually the most significant radioactive element. Clay minerals have the ability to concentrate potassium ions, thus the amount of gamma radiation in sedimentary rocks is a function of the content of clay minerals. Shales are characterized by the highest gamma radiation. A clay-contaminated sand, sandstone, limestone and evaporite will exhibit decreasing gamma radiations. As the individual clay minerals concentrate various amounts of Potassium 40, the radiation of different shale formations will not necessarily be the same. If a mud containing clay minerals is used as a drilling fluid, the radioactivity associated with the mud may complicate the interpretation. For these reasons, interpretation of gamma ray logs is restricted to the qualitative identification of rocks and their lithological and formational contacts.

TW3-72 penetrates a formation of alternating sandstone and shale layers. In utilizing the natural gamma ray log of TW3-72, a basic interpretational philosophy is used whereby shales are assumed to exhibit radioactivity maxima and sandstones to exhibit minima.

The two gamma logs in Figure 35 exhibit several distinctive maxima and minima. They were obtained by averaging radiation counts over an interval of time so that actual formation changes could be distinguished from statistical fluctuations

in the log. The amount of shift of the logs in the vertical direction, as a result of the time constant (the interval of time during which the integrator averages the counts received), was determined and the logs were adjusted vertically to conform to the scale of the other logs.

Geological Interpretation

In the gamma logs, the well casing is responsible for the large shift of the baseline to the right at a depth of 47.5 feet. Minima at depths of 24 and 38 feet probably correspond to gravel lenses in the overburden, while those at depths of 53, 58, 67, 75, 80, 93, 109 and 125 feet probably correspond to sandstone layers in the bedrock. The maximum at 17 feet probably corresponds to a silty sand. Maxima within the bedrock at depths of 72, 77, 85, 101, 110, 117 and 127 feet likely correspond to shales. The relatively small differences in magnitudes of both maxima and minima suggest that only slight lithological changes are present within the individual formations. All shales penetrated by the hole appear to be qualitatively very similar. The same can be concluded about sandstones below a depth of 90 feet.

Spontaneous Potential Log (SP Log)

A continuous record of variations in the potentials recorded by the downhole electrode is called the spontaneous potential (SP) log. The variations in the potentials are caused by the ohmic differences of potential in the well fluid column as a result of current flowing around interfaces of different formations.

In formations such as sandstone, the permeable beds are indicated on the SP log by curvature or slope changes characterized as minima. On the other hand, shales exhibit curvatures forming maxima. Formations such as limestone are characterized by straight portions in the SP log. The SP log often resembles the natural gamma ray log.

The shale baseline can be drawn through maxima on the right hand side of the SP log. A sandstone baseline, on the other hand, can be drawn through minima. If the salinity of the well fluid is constant, these baselines are parallel with each other and with the zero line.

Geological Interpretation

In Figure 35, the shale and sandstone baselines are neither parallel with each other nor with the zero baseline. The horizontal displacement of the baselines appears to increase

with depth. Sudden shifts can be observed in the lower part of the SP logs. These might indicate either a change in the salinity of the water in the well or a change in lithology or chemical composition of the shale and sandstone formations. As Figure 35 illustrates, the SP log exhibits a shift of both shale and sandstone baselines to more positive values at a depth of 110 feet. If the shales and sandstones below a depth of 110 feet had different compositions than those in the upper portion of the well, the shift could be attributed to these changes. It was concluded earlier, however, from the natural gamma log, that all shales in the well are qualitatively very similar and that sandstones below a depth of 90 feet also appear to be qualitatively similar. There are no changes or shifts in the natural gamma logs which would correspond to those documented in the SP log. The inclination of the baselines as well as the aforementioned shifts near the bottom part of the SP log are believed to be due to the increased salinity of the water with depth, particularly near the bottom of the well, rather than changes in the composition of the shales and sandstones.

Single-Point Resistance Log

This log represents a continuous record of the resistance between a grounded electrode on the surface and an electrode lowered into or raised out of the borehole. Having a relatively small zone of investigation, the single-point resistance technique is able to define thin beds in detail and accurately identify geological contacts. It generally provides only limited quantitative information on actual resistivities of the surrounding materials. The results are influenced by both the water in the borehole and the water in the formation.

Two resistance logs are presented in Figure 35. The one on the left-hand side was obtained on the way down the hole; the other on the way up. They are nearly identical in both shape and magnitude of deflections.

Geological Interpretation

In Figure 35, the resistance logs exhibit maxima at depths from 53 to 66 feet and at 82, 95, 106 and 126 feet. Maxima correlate well with minima in the natural gamma logs, with minima in the upper 105 feet of the SP logs, and with those portions of the well exhibiting no increase in diameter on the caliper logs. All these observations support the presence of sandstone beds. Similarly, minima on the resistance logs correlate well with maxima in the natural gamma logs, with maxima in the upper 105 feet of the SP Logs and with those portions of the well indicated by caliper as exhibiting increased well diameter, supporting the presence of shale beds.

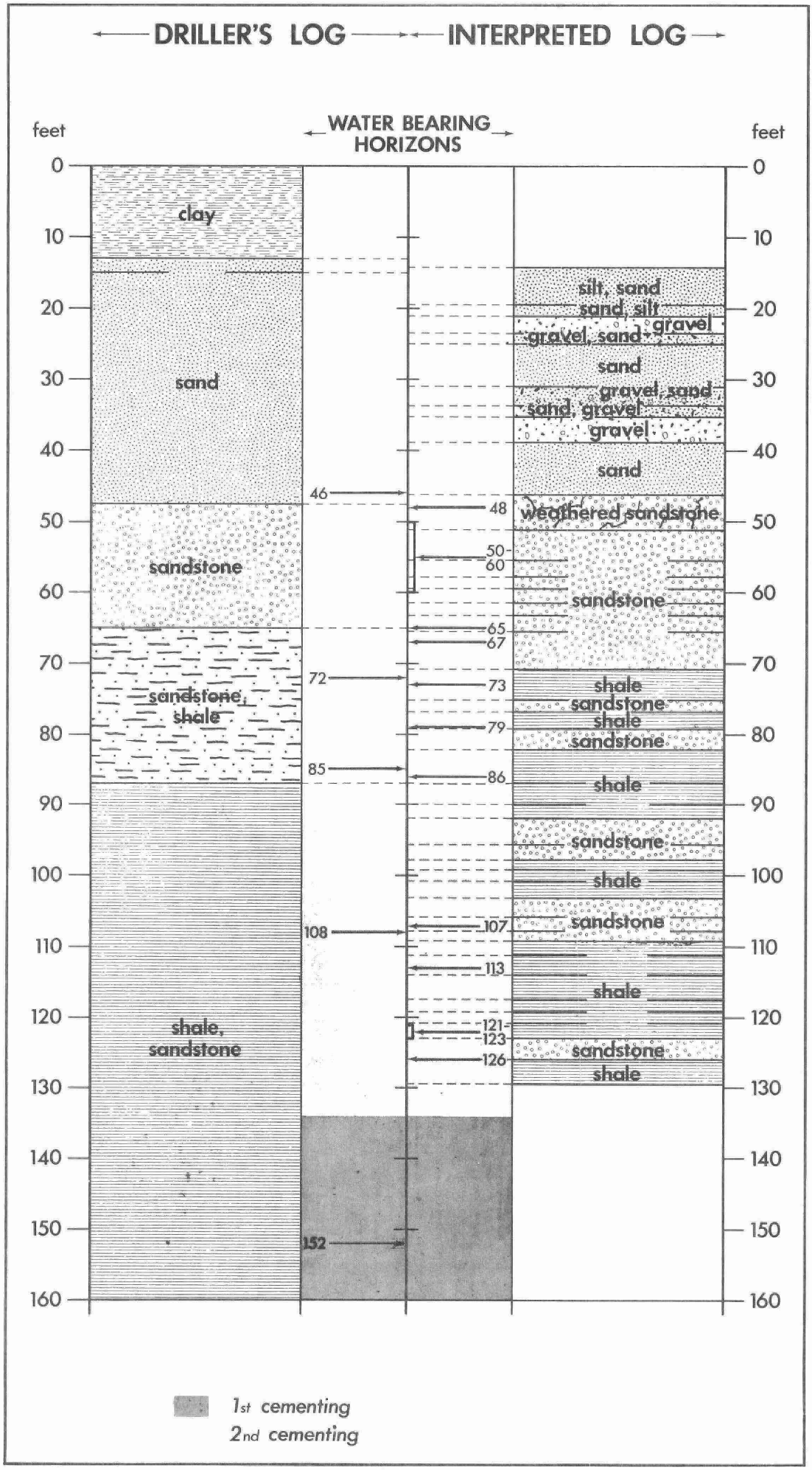

Figure 36. Correlation of geophysical well-logging results with driller's log.

There is a general decrease in the resistance as the depth increases. This decrease is likely due to the increasing salinity of the water toward the bottom of the well. The sandstone beds at 109 and 126 feet, indicated by minima in the gamma logs, exhibit resistances somewhat lower than those observed for the sandstones at 82 and 95 feet. If these beds were water-bearing horizons, then the resistance differences could be explained as being due to chemical differences in the water contributed by each zone to the well, with the water from deeper zones being more saline.

Lithological Log

The interpretation and correlation of geophysical logs presented in Figure 35 enabled the construction of a detailed lithological log of TW 3-72. In Figure 36, the lithological log is compared with the driller's log. They generally agree very well, although more detail is expressed in the lithological log.

DETERMINATION OF WATER BEARING ZONES

In order to determine water-bearing zones and allow for their relative quantitative comparison, temperature and flowmeter logs were obtained under various conditions in the well. These logs were then correlated with the caliper logs and with each other to provide information on the hydrologic characteristics of the well. The principles of these additional logging techniques, the corresponding logs and their interpretation are presented.

Temperature Log

A temperature log represents a continuous record of temperature changes of the water in the well with depth. A thermometer is slowly lowered into the hole in order that its sensitive unit has time to record the temperature of the adjacent water. A temperature log obtained in an undisturbed well is correlated with those temperature logs obtained during pumping or injection of water and with those obtained after pumping or injection was discontinued. Results of the correlation are then utilized in the identification of water-bearing zones and in an examination of their relative permeabilities (magnitudes of inflows).

Six temperature logs are presented in Figure 35. The two on the left-hand side, marked 1 and 2, were obtained while logging on the way down and up the hole, respectively. At that time, the water was pumped from the well at a rate of 8 gpm. The four other temperature logs were obtained at

specific time intervals (12 mins., 15 mins., 30 min., and 12 hours) after the pumping was discontinued. Unfortunately, a temperature log of the well under undisturbed conditions could not be obtained because testing activities were under way in the well at the time of the geophysical crew's arrival at the site.

Although the logging speed was kept constant in both directions, the logs obtained on the way up differ from those obtained on the way down. While the downhole temperature measurements represent real temperature differences in the well-fluid, the uphole measurements probably represent values as a result of mixing of the fluid due to perturbing effect of the cable and the probe. Therefore, only the temperature logs obtained on the way down hole (curves 1, 3 and 6 in Figure 35, marked by arrows pointing down) were used for the interpretation.

The character of some temperature logs can be used for interpretation. If, for instance, a consistent increase in temperature with depth as a result of the geothermal gradient is discontinued, it may indicate a zone where water enters or is obtained from a permeable horizon, or where water from a lower aquifer begins to influence the readings. If the temperature does not change with increasing depth, inter-aquifer circulation may be indicated. A local anomaly in a temperature log may indicate a cross-flow, if there is little or no vertical movement of water in the well.

Interpretation

Temperature logs 1, 3 and 6 show zones of temperature development at several depths, i.e. at 48, 65, 73.5, 80, 85, 109, 114 and 125 feet, respectively. These zones indicate the presence of several water-bearing horizons at corresponding depths in the well. Zones at 48 and 109 feet can be clearly observed in all three temperature logs and appear to be the most important ones. The last temperature log, taken 12 hours after the pumping was discontinued, suggests a vertical flow from the water-bearing zone at a depth of 48 feet to that at a depth of 108 feet. Relatively cooler water appears to be contributed by the horizon at a depth of 65 feet.

Flowmeter Log

A flowmeter log is a continuous record of vertical movement of water in a well. Logs used for this study were obtained by an impeller flowmeter. The number of impeller revolutions per unit time corresponds to the velocity of moving water in the well. The flowmeter is lowered down or up the hole at a constant speed. Changes in water movement result in an

increased number of revolutions proportional to the speed of the movement. Thus, the recorded flow represents not only the real flow but also the simulated flow due to lowering of the flowmeter in the hole. In order to intensify the flow against water-bearing zones, water is usually pumped from a well. By injecting water into a well an artificial flow is also established. Assuming that the water-bearing zones are able to take as much water as they can contribute, a decreased movement would be encountered below these zones.

The flowmeter logs need to be corrected for variations in the diameter of the well. For this purpose, a correlation of flowmeter logs is usually made with caliper logs. The flowmeter used in TW3-72 was not calibrated; therefore, the results are relative and can only be interpreted qualitatively.

Interpretation

Several flowmeter logs were obtained in an attempt to identify the water-bearing zones in the well by correlation with the temperature logs. The logs obtained while water was pumped from the well at the rate of 8 gpm and while the well was at rest did not indicate any appreciable changes in the recorded flow and for this reason the results were not included in Figure 35. Because a higher capacity pump was not available, it was decided to inject water at higher rates into the well. The flowmeter logs in Figure 35 were obtained during an injection of 30 gpm of water into the well, and each log was obtained with a different sensitivity of the logger. The log deflections to the right correspond to an increased flow. The increases in flow, however, may be due to either a real interaquifer flow or to a locally small diameter of the well.

The flowmeter logs were correlated with the caliper logs to eliminate changes in flow due to variations in the diameter of the well. The zones of increased flow interpreted as potential water-bearing zones are listed in Table 3. Except for the zone near 48 feet, these interpreted zones of increased flow may be subjected to dispute, as the character of the logs changes little at the corresponding depths. These zones were correlated with the zones of temperature development described earlier in an attempt to identify and classify the water-bearing zones. Results of the correlation are also presented in Table 3.

It can be observed that the zones of increased flow in Table 3 correlate well with the zones of temperature development, thus supporting their interpretation as possible water-bearing zones. Some of these zones appear to be good water contributors as, for instance, that zone from 48 to 60 feet, which is believed to contribute about 40 percent of the total capacity of the well.

TABLE 3

Zones of Increased Flow Depth (ft) From	- To	Zones of Temperature Development (ft)	Material	Water Bearing Zone	Relative Magnitude of Contributors %
47	48	48	Weathered SNDST	Yes	40%
50	60		SNDS	Yes	
65	67	65	SNDS	Yes	weak
72	74	73.5	SHLE-SNDS interface	Yes	weak
79	80	80	SHLE-SNDS interface	?	?
86	87	85	SHLE-SNDS interface	Yes	weak
107		109	SNDS	Yes	intermediate
111	113	114	SHLE	Yes	weak
121	123	125	SHLE-SNDS interface	Yes	intermediate

SUMMARY AND CONCLUSION

The comparison of the water-bearing zones determined from geophysical logs with those recorded by the driller is presented in Figure 36.

The interpretation of geophysical logs suggests that the zones above a depth of 100 feet appear to be responsible for most of the well capacity. The major water-bearing zone at the depth of 48 feet corresponds with the bottom of the casing or top of the bedrock surface. This indicates that the weathered surface of the sandstone bedrock is a highly permeable zone supplying a considerable amount of water to the well. Some other apparently minor water-bearing zones correlate with shale-sandstone boundaries.

The SP and single-point resistance logs appear to indicate an increase in the salinity of the water with depth and particularly below a depth of 110 feet. Thus, one or more of the water-bearing horizons below this depth appeared to contribute poor quality water to the well.

After an examination of the available evidence, it was felt that by cementing off the water-bearing horizons below 105 feet, the quality of the water pumped from the well would be improved, while the specific capacity would not be significantly reduced. The well was cemented by the driller to a depth of 92 feet and again re-tested. Figures 37, 38, 39, 40 and 41, taken from the consultant's report (Clister, 1972), compare the results of various tests carried out in the well before and after the last cementing to a depth of 92 feet. Graphs in Figure 40 illustrate the decrease in the specific capacity of the well due to cementing. The decrease appears to be about 48% at a pumping rate of 40 gpm. The graphs in Figure 40 were constructed using the corrected drawdowns determined by the consultant and expressed graphically in Figure 39.

As anticipated, the water quality improved considerably after the recommended cementing was completed. The improvement in water quality is documented in Figure 41. It illustrates that the chloride concentrations were much higher before than after cementing. No increase in chloride concentration with time and pumping rate was observed after cementing, thus indicating that the water-bearing zones contributing the poor quality water to the well were successfully grouted.

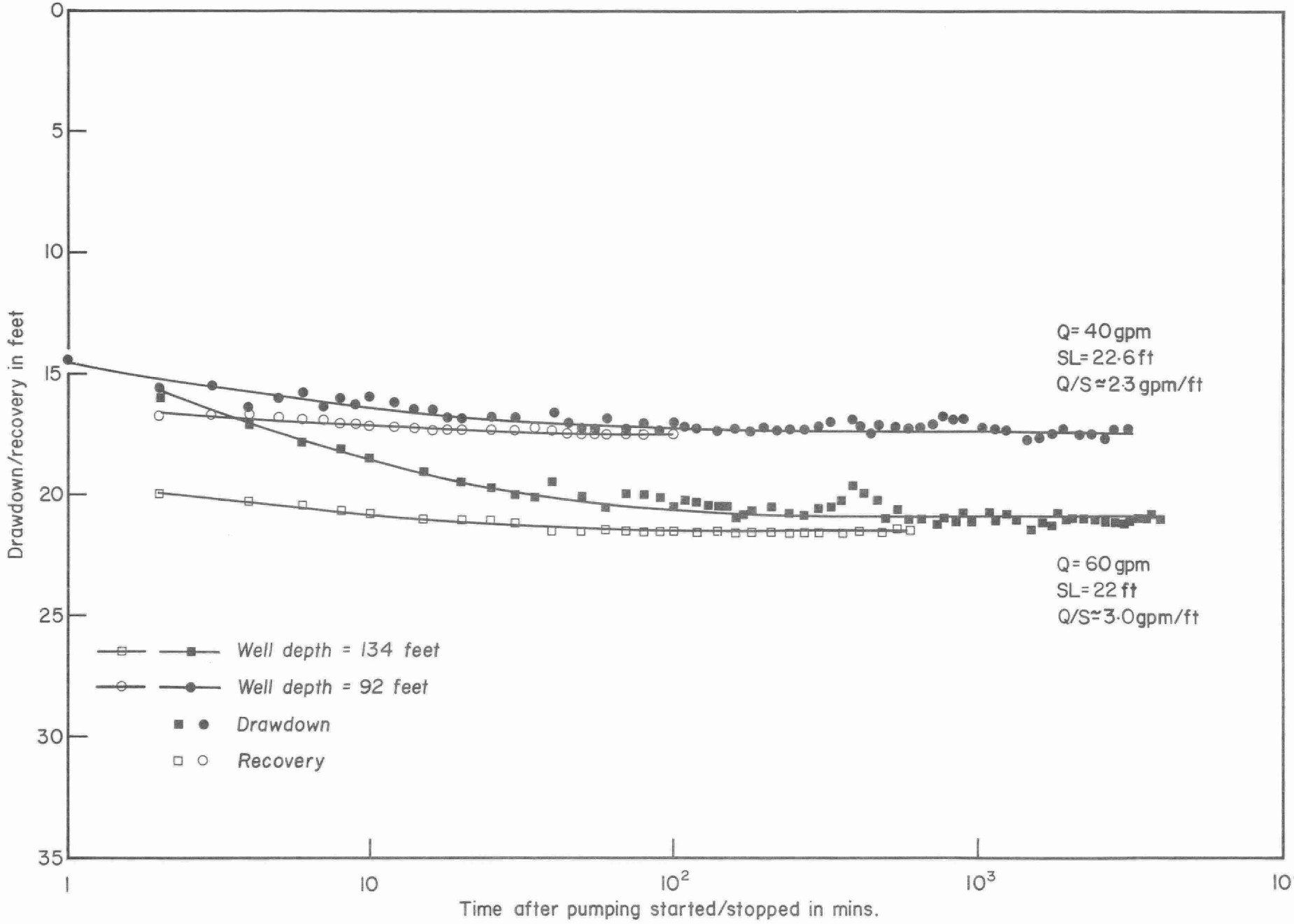

Figure 37. Pumping tests before and after cementing.

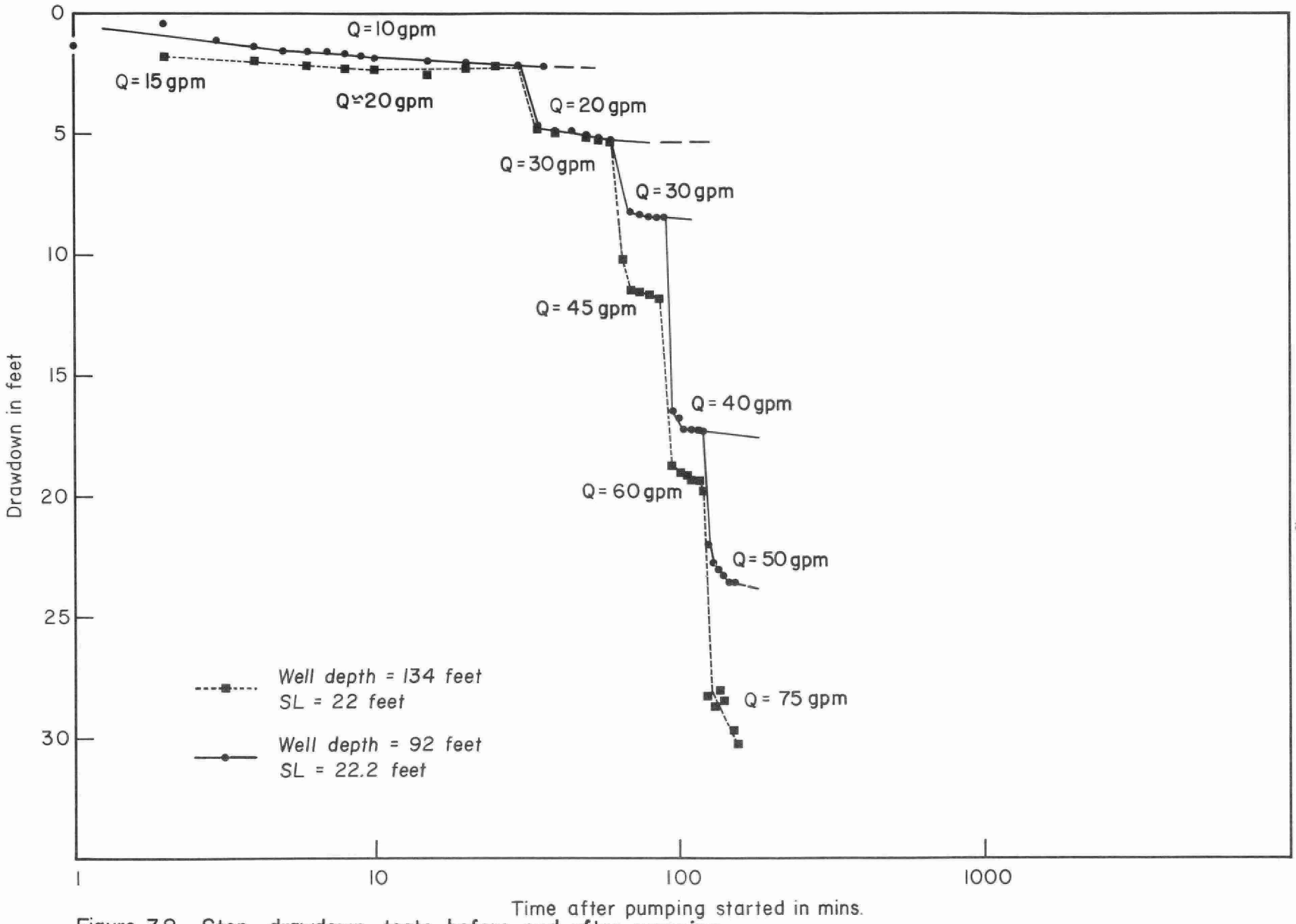

Figure 38. Step-drawdown tests before and after pumping.

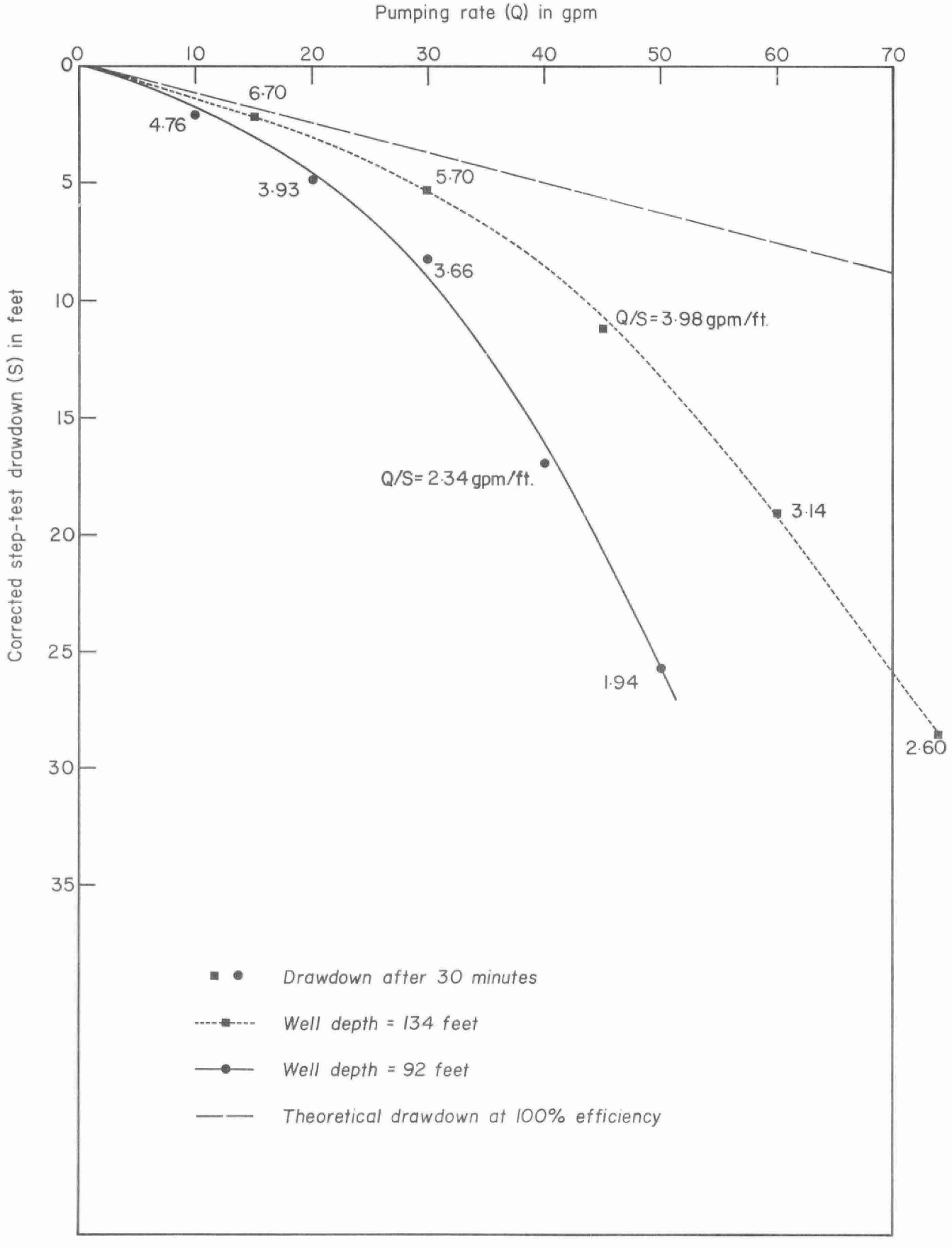

Figure 39. Changes in well characteristics as a result of cementing, corrected step-down curves.

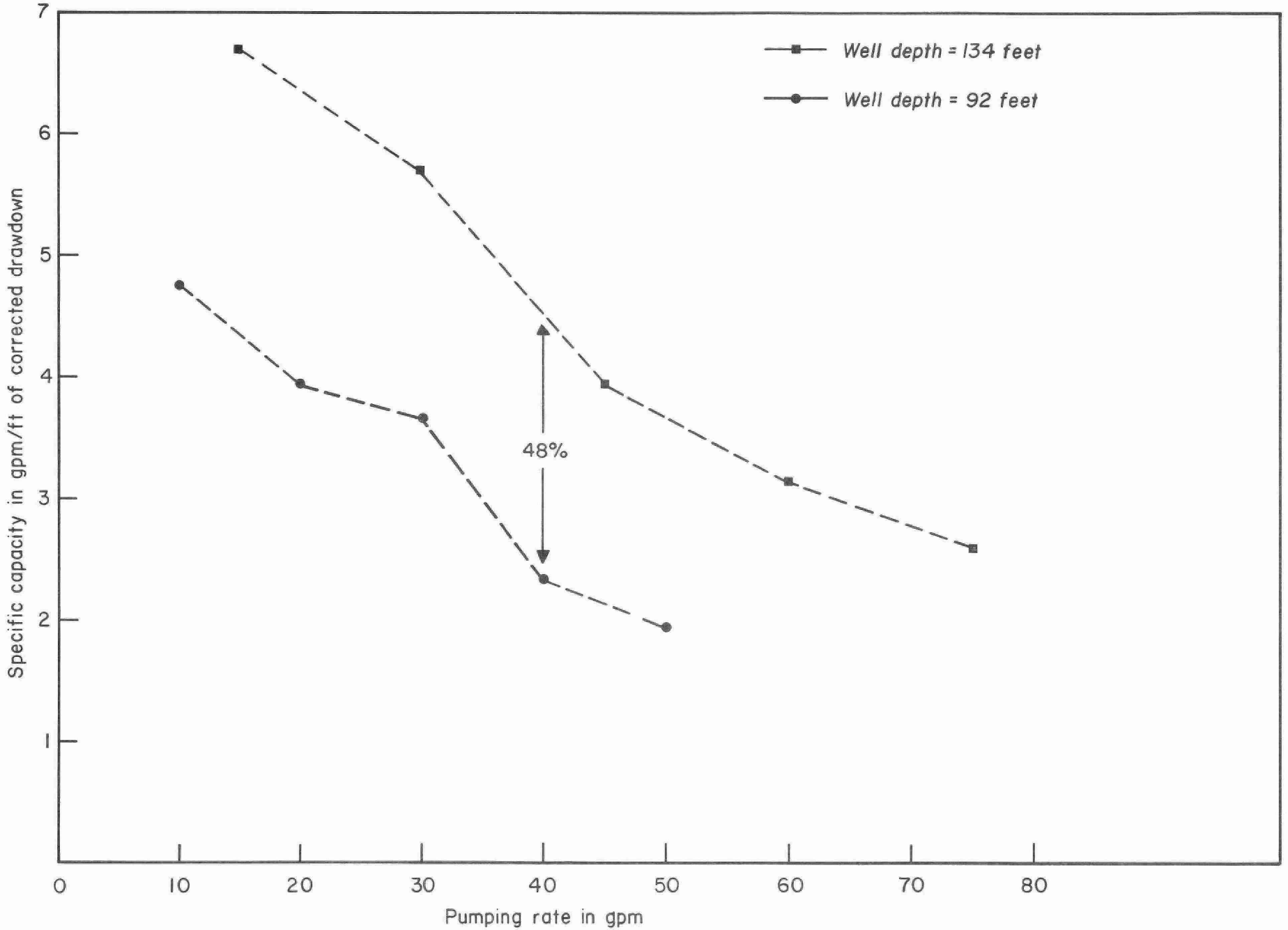

Figure 40. Changes in well characteristics as a result of cementing, 2 specific capacity curves.

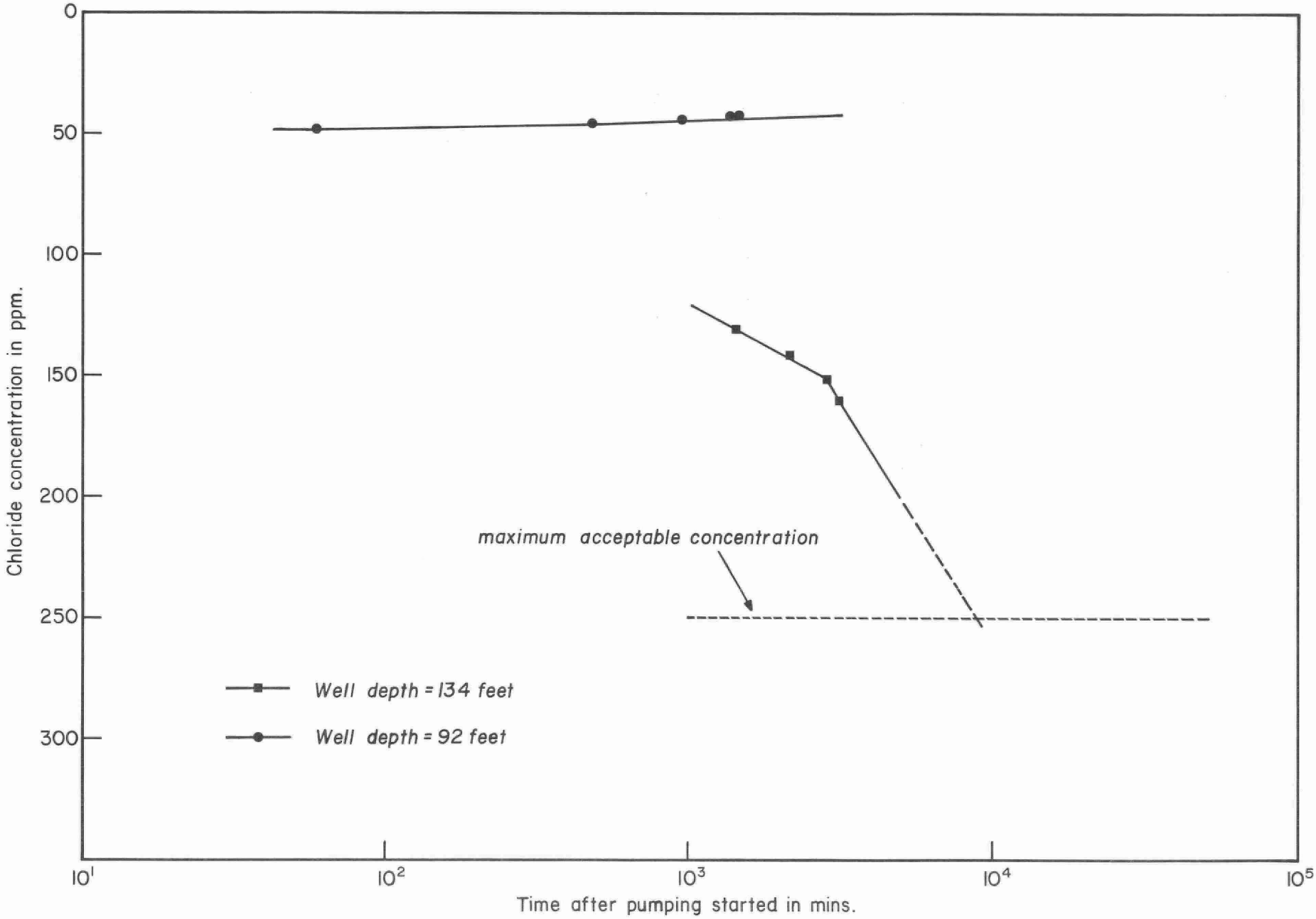

Figure 41. Comparison of chloride concentrations before and after cementing.

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For Further Reading

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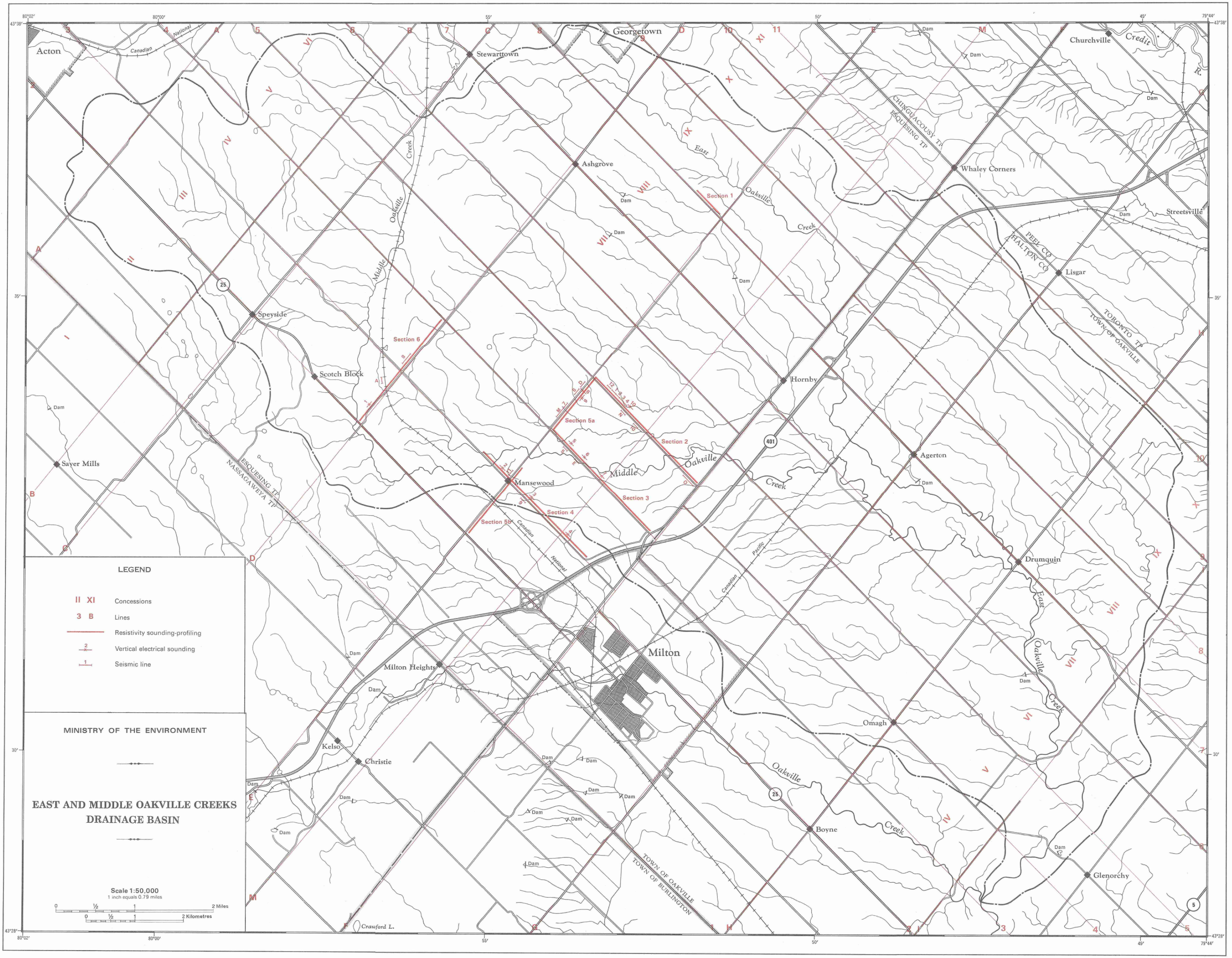

Figure 2. Location map of geophysical investigation sites.

CAZON
EV.661

WØ5

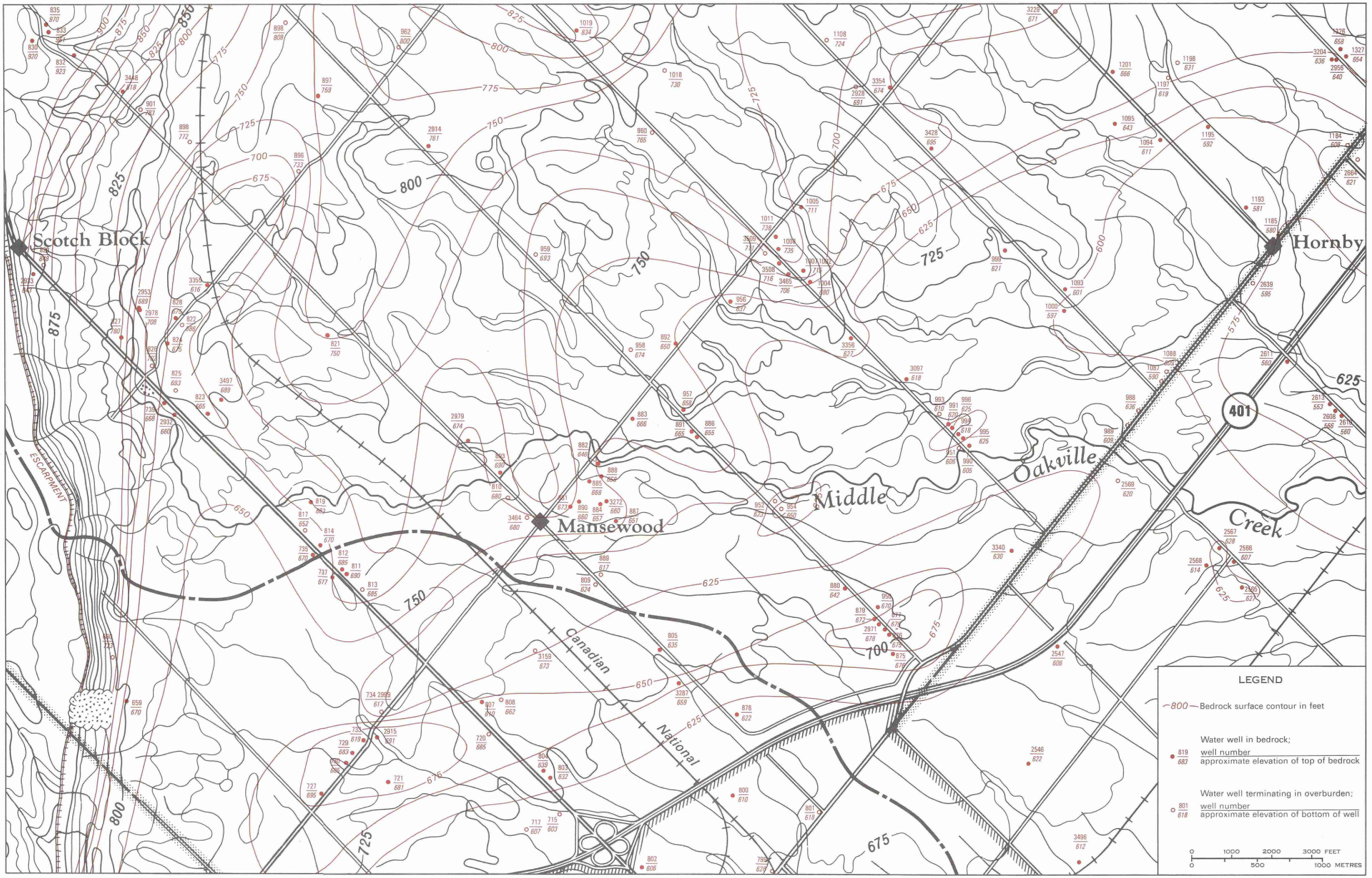

Figure 3. Bedrock topography and well locations in the investigation area.

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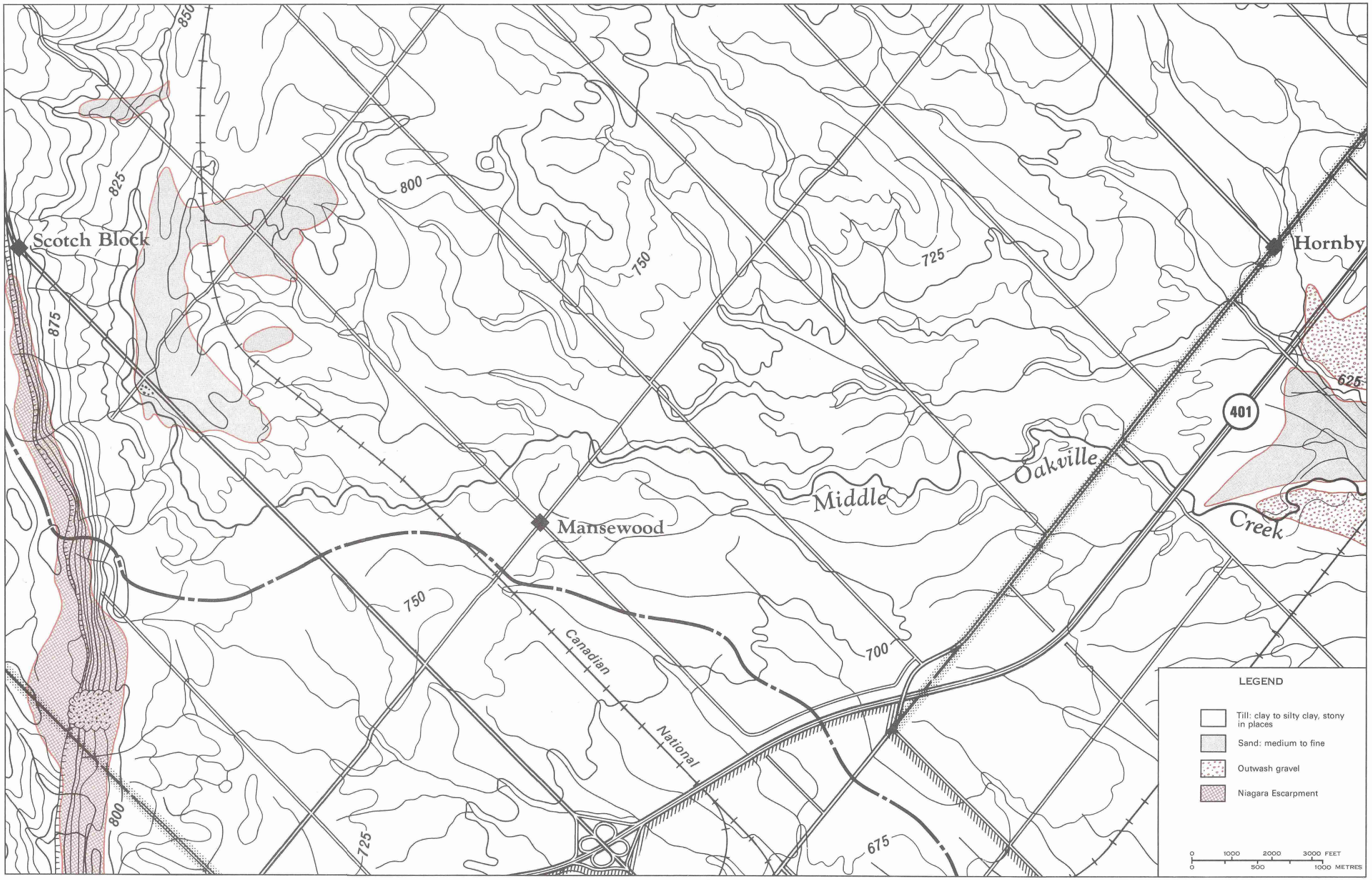

Figure 4. Surficial geology in the investigation area.

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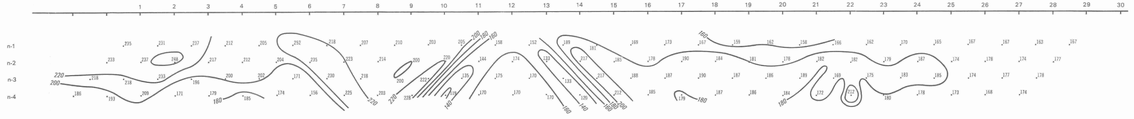
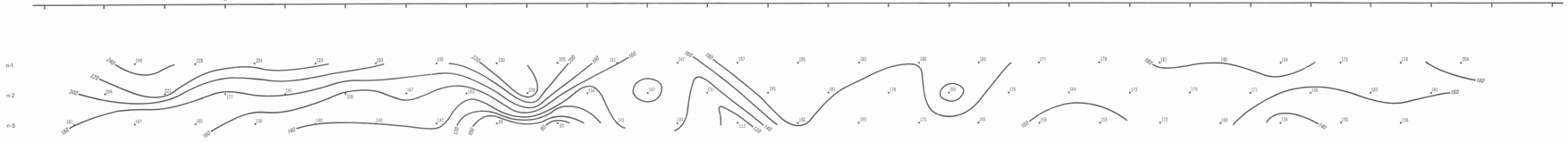
COLLINEAR—DIPOLE ELECTRODE SPACING

x=25′

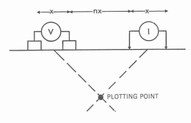
x=50′



x=100′



ELECTRODE CONFIGURATION



X=25′
X=50′
X=100′

LEGEND

- Till
- Gravel
- Sand
- Clay
- Queenston Shale

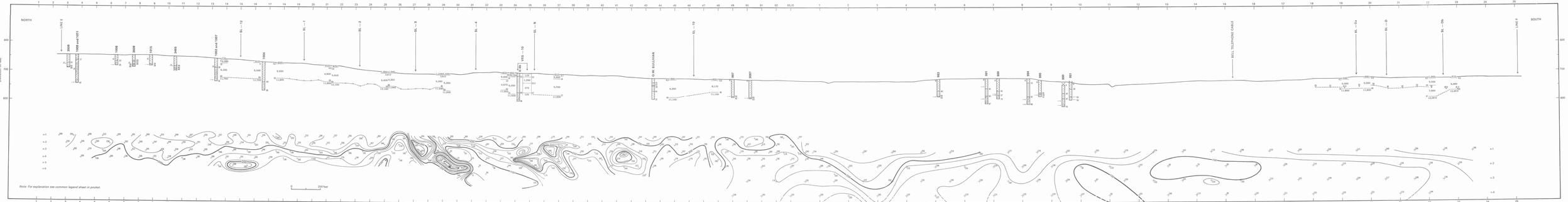
Depths in feet
Frequency: 0.31 c.p.s.
Contour interval: 20 ohm feet

0 100 200 feet

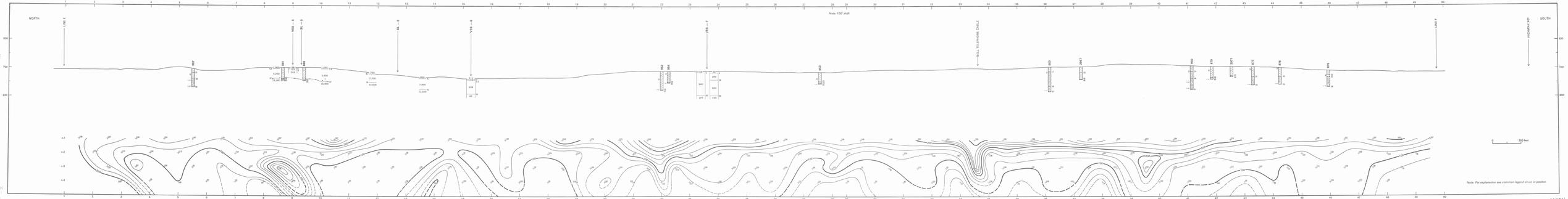
Section 1. Comparison of results obtained by collinear-dipole electrical profiling at the test site in Oakville Creek basin.

CAZON
EV.661
W85

CAZON
EV.661
W85

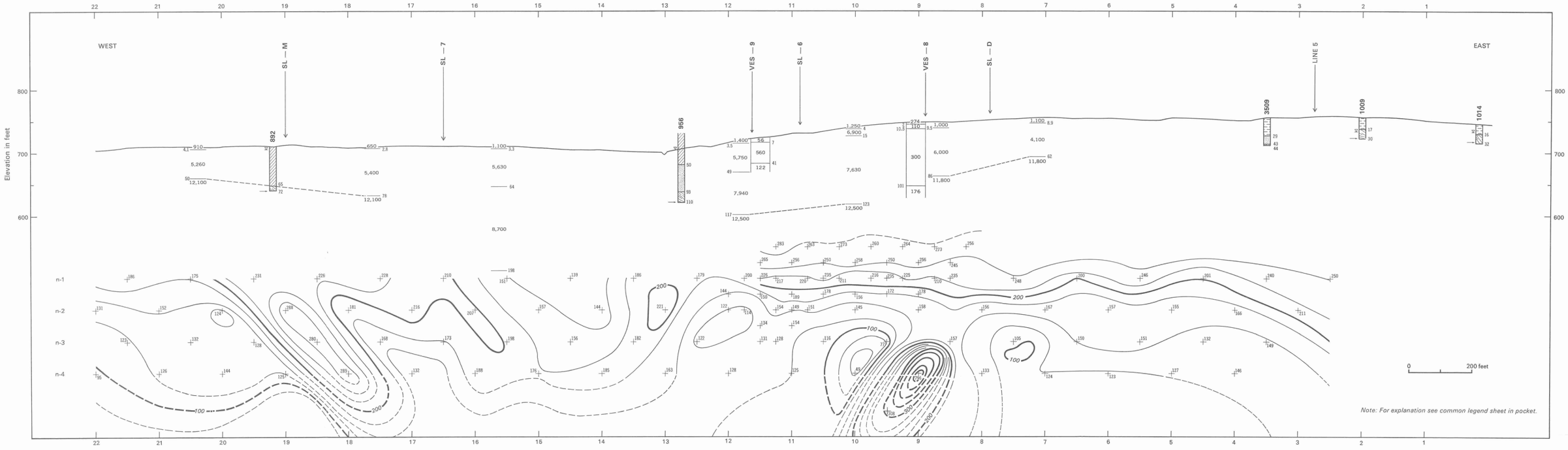


Section 2. Cross-section of drillers' logs of water wells and results of geophysical investigations.



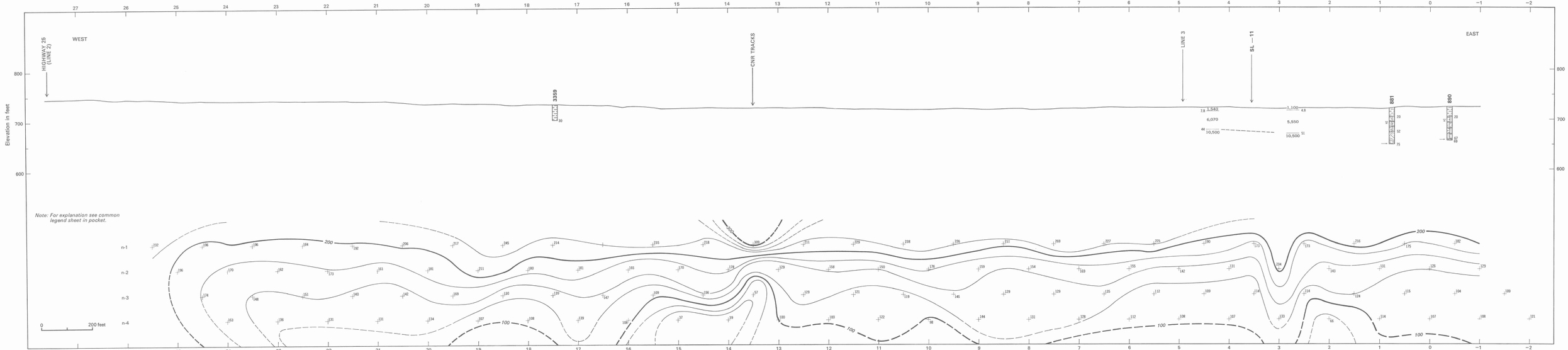
Note: For explanation see common legend sheet in pocket.

Section 3. Cross section of drillers' logs of water wells and results of geophysical investigations.

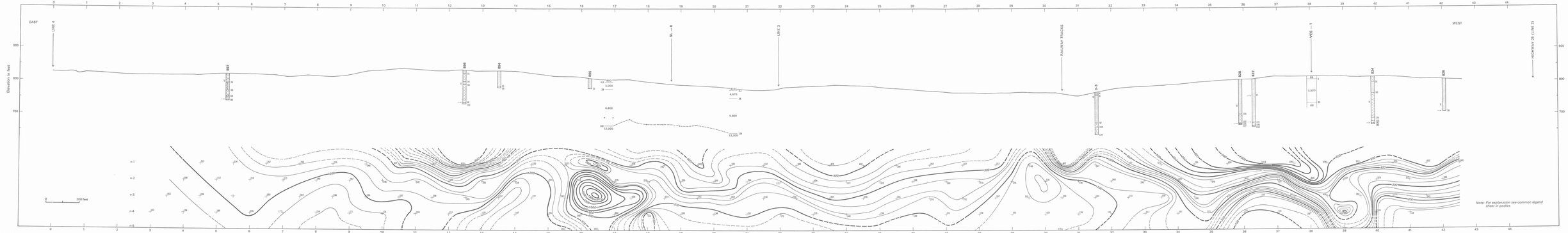


Section 5a. Cross-section of drillers' logs of water wells and results of geophysical investigations.

CA2ON
EV.661
W05



Section 5b. Cross-section of drillers' logs of water wells and results of geophysical investigations.



Note: For explanation see common legend sheet in pocket.

Section 6. Cross-section of drillers' logs of water wells and results of geophysical investigations.

CA20N EV461 W05

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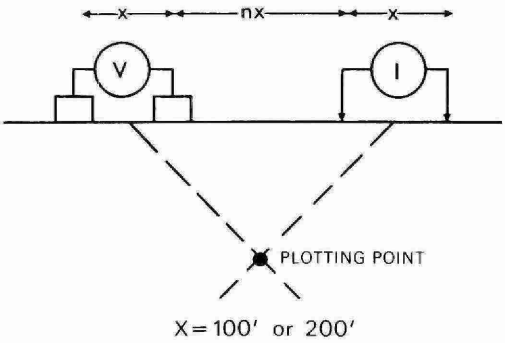
LEGEND FOR SECTIONS 2 TO 6

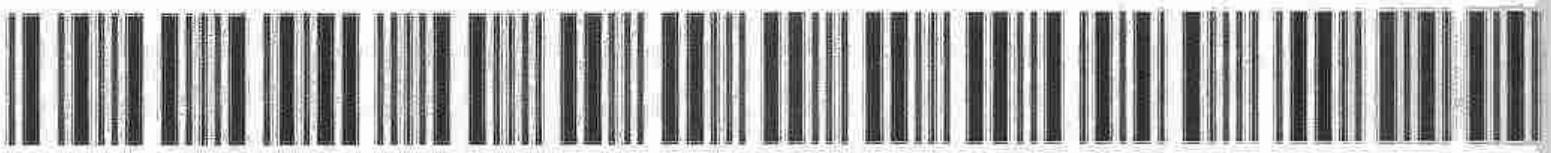
Electrode configuration:



X = 100′ or 200′

- Till
- Gravel
- Sand
- Clay
- Queenston Shale

Depths in feet
Velocities in feet/second
Resistivities in ohm-feet
Contour interval: 25 ohm-feet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